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THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

Line Heating

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Todd Pacific Shipyards Corporation

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FOREWORD

A *product work breakdown is* the framework of any shipbuilding system which features organized production lines based on the principles of group technology. *Statistical control of accuracy is* the means used to continuously improve a system by optimizing design details, work methods and dimensional tolerances. *Line heating is* the work method specifically developed to productively achieve the tolerances so identified. The three disciplines are interdependent.

"The key to rapid construction is how to weld without distortion . . ." said Elmer L. Harm, the former Kaiser manager who directed the 1951-1961 National Bulk Carrier shipbuilding effort in Japan. Japanese managers regard that venture as the starting point of modern shipbuilding technology. Locked-in stresses produced by forces needed to fit inaccurate parts were identified as a major cause of distortion. Line heating developments followed, aimed at both achieving better accuracy when shaping curved parts and removing distortion from subassemblies immediately after their manufacture.

This approach led to the development of remarkable line-heating aids and work instructions by Ishikawajima-Harima Heavy Industries (IHI) as described herein. In contrast traditional shipbuilders, because they are not product oriented and because they are not guided by statistical analyses, cannot fully exploit line heating. Their notion that accuracy in-process entails high costs is negated by the higher costs of dealing with distortion in succeeding assembly work particularly in a building berth. There, fitting and welding costs are compounded.

This book is for shipbuilding engineers/managers, particularly shop managers and their deputies, who need to acquire an understanding of all facets of a shipbuilding system. Descriptions of pertinent control experiments convey the basis for scientifically applied line heating. They also provide useful background for future developments. These could include similar control experiments for the high-yield steels used exclusively in naval ships, evaluation of laser-applied heat, and computers to generate heat lines and to control line-heating operations.

Practical information is included about approvals (line heating is permitted for *all* ABS grades of steel), lofting preparations, tolerances and methods. Traditionalists may be familiar with or only have an interest in some of the distortion-removal techniques described in Chapter 4.0. The Pictorial Summary, Chapter 5.0, should convey to anyone concerned with improving productivity, the crucial role of line heating both for shaping parts and for removing distortion from subassemblies immediately after their manufacture.

During the November 1982 IHI Technology Transfer Seminar, Avondrde Shipyards reported that costs associated with conventional furnacing were 60 man-hours to manufacture each required plate-forming jig and an average of 16.6 man-hours for forming each plate. For a second multiship contract following the introduction of line heating in conjunction with a product work breakdown and accuracy-control measures, direct labor costs dropped to 10.0 man-hours per plate for the second ship. This decrease of nearly 40% *exclude-s* savings associated with elimination of plate-forming jigs. Further, it *excludes* significant savings associated with the contribution of line heating to the rapid execution of assembly work in organized production lines.

ACKNOWLEDGEMENTS

L.D. Chirillo Associates, Bellevue, Washington produced this book for Todd Pacific Shipyards Corporation, Los Angeles Division.

The material on which this book is based was compiled by a project team led by S. Nakanishi, International Division, Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) of Japan. Team members included T. Yamamoto, T. Hamasaki and S. Okubo. Their work was significantly edited by L.D. Chirillo assisted by R.D. Chirillo.

Appreciation is expressed for assistance received from S. Kohata and S. Saito of II-H's Tokyo Shipyard. Also, appreciation is expressed to Y. Ichinose of IHI Marine Technology and to T. Lamourex, L. Willets, D. Arnold and B. Coralles of Todd's Los Angeles Division, who furnished essential support.

This book is an end product of one of the many projects managed and cost shared by Todd for the National Shipbuilding Research Program. The Program is a cooperative effort by the Maritime Administration's Office of Advanced Ship Development and the U.S. shipbuilding industry. The objective, described by the Ship Production Committee of the Society of Naval Architects and Marine Engineers, is to improve productivity.

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1.0 INTRODUCTION[1]

1.1 Significance

The many different parts and subassemblies which characterize shipbuilding impose difficult manufacturing problems because they are required in mixed quantities. In the past most were custom manufactured with relatively great dependence on experienced people.

Now, competitive shipbuilders apply planning methods which separate the many different parts and subassemblies by the problems inherent in their manufacture. Planning is refined so that within each problem category, work packages having the same work content individually address either a group of items or a single entity to be manufactured. This is group technology.

Such work packages are executed in real or virtual flow lanes each having just the worker skills and facilities necessary for a specific problem area. Thus, by prudent division of labor and machinery, less skilled people are now employed and the benefits of mass production are obtained. Significant cost-savings are derived from just-in-time manufacture of interim products needed for subsequent assembly work. However, the benefits would be greatly diminished if there were need to perform rework.

The most significant shipbuilding problem, commonly encountered, is difficulty in joining blocks during hull erection due to inaccuracies such as in overall block dimensions and misalignment of structural members. During block assembly traditionalists provide extra material, i.e., margins, and defer certain welding such as ends of longitudinals to shell. Their subsequent marking and trimming when erecting the hull is rework. Their cost for safely performing the deferred welding at the building site, is at least three times more than the cost for the same welding during block assembly.

In order to avoid such problems, competitive shipbuilders scientitlcally apply statistical control methods to *regulate accuracy* in each work stage, e.g., layout, fitting, welding and distortion removal. Thus, accumulated variations for the erection process are limited within tolerances which insure structural integrity and which facilitate joining complete blocks with minimal rework such as gas cutting and back-strip welding.

Secondly, but no less important, statistical control of accuracy is a means for regulating the amount of work performed at each stage. Thus, out-of-tolerance work is not arbitrarily passed downstream where it would eventually cause more serious disruption. For this reason and because there is considerably less rework, productivity is enhanced.

Line heating, the process of forming shapes by controlled heating and cooling, is a necessary adjunct to accuracy control. Line heating is relatively safe and features nominal facilities investment, improved accuracy and increased productivity when prudently used in conjunction with existing presses and rollers. Line heating is also scientifically applied by competitive shipbuilders for removing distortion from parts, sub-blocks and blocks.

With group technology and accuracy control, line heating is means for converting much of the rework and deferred work which traditionalists perform at the erection site into safer, easier and less work. Moreover, this transformed work is more evenly distributed over all preceding processes for hull construction including designing and lofting.

Shipbuilders who apply line heating as a science:

- eliminated need for furnaces and diverted some work from heavy-bending facilities,
- enhanced safety,
- more accurately bend shell plates and longitudinal stiffeners,
- achieve more consistent accuracy and better schedule adherence,
- employ less-skilled workers with more assurances for quality than had they retained experienced blacksmiths who “furnace” parts red hot for hammering into shapes while having to compensate for possible losses in thickness and strength,
- fit curved stiffeners to bent-shell plates with minimal force to avoid distortions caused by welding stressed components,
- are not limited by furnace size and therefore employ larger-size plates in order to reduce welding requirements, and
- facilitate subsequent assembly work by eliminating distortion during each manufacturing level so that all interim products, e.g., parts, sub-block and blocks, are within tolerances optimized for productivity purposes.

[1]Most of this chapter is based upon an interpretation of "Line Heating Method - A New Technique Taking the Place of Smith Work" by T. Hashimoto for the 60th Anniversary Series, Volume 5, The Society of Naval Architects of Japan, 1961, pp. 53-71.

Thus, line heating greatly contributes to elimination of much traditional erection work which is redundant, corrective or inherently unsafe and inefficient, such as:

- extensive alignment of butts, seams and internal structural members with dogs, clips, wedges, hydraulic jacks, special staging, etc.
- gas-cutting for adjusting erection joints,
- cutting free, realigning and rewelding previously assembled parts, and
- removing dogs, clips, yokes and lugs and restoring surface finishes.

With erection work so minimized, less time is needed for the duration between keel laying and launching of a ship. As a ship-erection site and associated facilities usually represent a great capital investment, their availability for reuse as much as possible in a given time span is a singular element of competition.

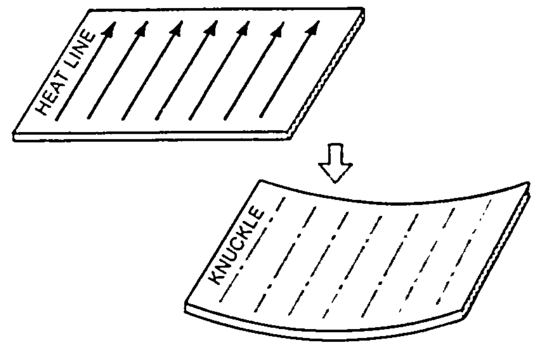


FIGURE 1-1: The curvature achieved by line heating is the same as if the plate was worked slightly with a press except that some shrinkage occurs.

1.2 Principle

The fact that stress is induced in a steel plate when part of it is heated is well known. When such stresses are controlled it is possible to produce strain, i.e., permanent deformation, just as if mechanical forces were applied. Similarly, thermally induced stresses can be used to remove strain, i.e., to eliminate distortion. Herein lies the idea of controlled heating and cooling for regulating strain so as to achieve a specified curvature or for removing undesired curvature.

When a plate is heated along a line, such as with a torch, it will upon cooling bend so as to form a slight knuckle along the line. When the heated areas are cooled with water as the torch progresses, the bending effect is more evident. The curvature achieved is the same as if the plate were worked slightly with a press except that some shrinkage occurs; see *Figure 1-1.* Such heating can be applied in all directions many times over, or between or on bends formed by previous heating.

What actually happens is illustrated in *Figure 1-2.* Local heating creates thermal stress in a very small region. Young's Modulus and the Elastic Limit of the effected material both decrease with the rise in temperature. As the heat source travels, the adjacent material even if not cooled with water remains cool enough to resist the thermally created stress. So constrained, the heated surface swells beyond its Elastic Limit and therefore after cooling retains some minute deformation. During the cooling process, the bulge-side surface contracts more than the other side resulting in angular distortion (bending) and some amount of overall shrinkage.

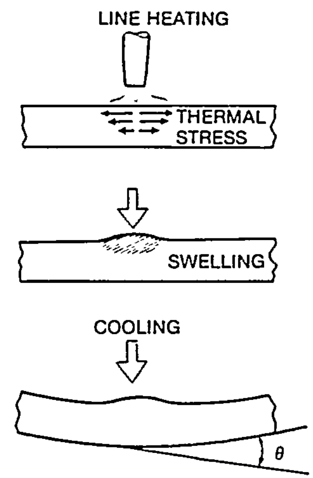


FIGURE 1-2: Local heating creates thermal stress in a very small region. Torch travel is in a direction toward the observer.

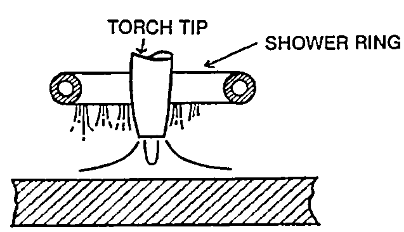


FIGURE 1-3: When line heating was first systematized for creating curvature, shower rings were tried. Subsequently a single water-stream in tandem so as to follow the torch was found to be more effective.

The effect of heating is usefully categorized in accordance with three ranges of increasing-heat input as follows:

Heating Range	*Effect on Material*
1st	little
2nd	same as for cold working
3rd	significant

Clearly, the selection of a heating range or a combination of ranges and the controls that should be applied, must be based upon the needed assurances for material strength and toughness after line heating.

1.3 Fundamentals

A study for plate bending by line heating is known to have been reported in 1956. Fundamentals for practical applications were published in 1961 and, as described in the following, were based upon use of an oxy-acetylene torch for applying heat to ordinary mild steel. As shown in *Figure 1-3*, water cooling was provided by a shower ring fixed to surround the burner tip (subsequent to this experiment a single water stream in tandem so as to follow the torch was found to be more effective).

Mechanization wherever possible is preferred because it facilitates control. This means automatic regulation for maintaining the constancy of certain critical aspects, e.g.:

- the distance between a torch tip and a steel plate,
- gas, oxygen and water flows, and
- travel speed of the torch.

Further, the degree of curvature obtained for each heat line and the shrinkage which occurs both vary with other factors such as:

- plate thickness,
- material type, and
- degree that stress is mechanically applied before line heating.

Thus, process standards are virtually prerequisite. If relatively inexperienced people are assigned, such standards are essential.

The factors which govern the rates of heating and cooling are the main determinents for the degree of deformation (bending) which occurs. These factors are:

- torch-tip type and size,
- distance between torch-tip and plate,
- torch travel speed,
- cooling method (water or air),
- rate of applied coolant,
- distance between heating center and cooling center, etc.

Among other factors, only externally applied forces which create initial stresses are regarded as significant.

Considering the many types and thicknesses of materials used in shipbuilding, regarding torch speed as the principal factor is most practical. This permits great simplification of the needed combinations of other factors. For example with torch speed as the only variable, the single combination of other factors shown in *Figure 1-4* can be used to bend mild steel ranging in thickness from 10 to 25 millimeters.

Oxygen pressure and quantity: 4.1 kg/cm²; 2200 l/k @ 0°C

Acetylene pressure and quantity: 110 mm Hg; 1770 l/h @ 0°C

Size of torch tip: #40 (3.35 mm ϕ)

Tip height and angle to plate: 16 mm; 90°

Cooling method and water quantity: shower ring; 2 l/min

FIGURE 1-4: An experiment showed that with torch speed as the only variable, a single combination of other factors can be used to bend mild steel ranging in thickness from 10 to 25 millimeters.

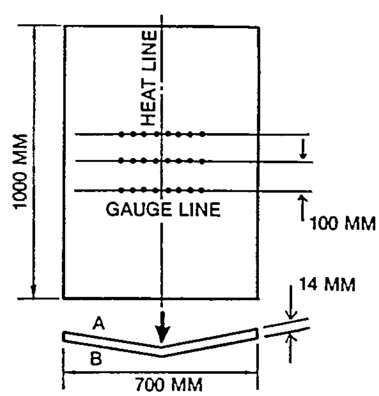


FIGURE 1-5: An experiment to determine shrinkage of mild steel by line heating used the combination of factors listed in *Figure 1-4*. Data was recorded for torch travel speeds of 2.5, 5.0, 7.5, 10.0, 12.5 and 15.0 mm/sec. Shrinkage gauges, each 20 mm long, were placed on both sides of the plate along three gauge lines.

1.4 *Shrinkage and Bending Effect*

The effect which results in bending is caused by unbalanced shrinkage. An experiment, described in *Figure 1-5,* identified the relationship between shrinkage and bending effect and also disclosed that there is accompanied total shrinkage. Featuring various travel speeds, the experiment proved, as shown in *Figure 1-6,* that:

Ž at very low speeds (high temperatures), total shrinkage is great and the bending effect is small,
Ž as speed increases, shrinkage reduces exponentially while the bending effect increases relatively fast, passes through a maximum value, and thereafter reduces gradually.

As further shown in *Figure 1-6,* there is only a limited useful range of speeds at which both acceptable shrinkage and near maximum bending effect are obtainable.

1.5 *Measurement of Bending Effect*

Additional control experiments disclosed how line heating effects curvature. The factors listed in *Figure 1-4* were held constant while others were varied as follows:

Ž plate thickness (t): 8, 14 and 18 mm,
Ž travel speed (v): 5, 10 and 15 mm/see, and
Ž initial stress (σ_S) : 0, —8, and - 16 kg/mm^2.

In each case the initial stress was mechanically applied and a strain gage was used to confirm that the desired surface stress was achieved at the heating line. Pertinent dimensions, heating-line orientation and dial-gage lines (for measuring angular displacement) were as illustrated in *Figure 1-7.*

The curves of bending achieved by line heating are contained in *Figures 1-8, 1-9 and 1-10.* The following observations are noteworthy:

Ž the angular distortions (bending) shown in *Figure 1-8,* particularly for t = 14 mm, are clearly related to the bending affect as plotted in *Figure 1-6,* and
Ž the existence of initial stress as shown in *Figure 1-9* and particularly the increased stress shown in *Figure 1-10,* result in remarkable degrees of permanent deformation after line heating.

Obviously, applied initial stresses greatly facilitate bending by line heating.

1.6 *Other Variables*

Addressing various plate thicknesses by adjusting only initial stresses and torch travel speed as a means to control bending would be ideal. However, this requires maintaining other factors in an exact relationship which, while feasible for laboratory experimentation, is not practical in real production situations. Therefore, an additional experiment was performed for the purpose of learning the behavior of the bending effect when other factors varied. The resulting knowledge is the basis for establishing practical tolerances.

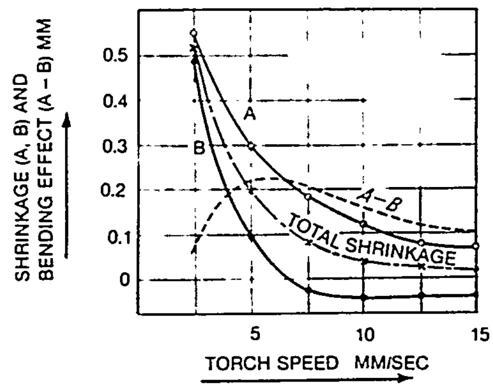


FIGURE 1-6: Bending effect is defined as the difference between shrinkage of the heated side (A) and shrinkage of the other side (B). The shaded area designates the limited useful range of torch speeds at which both acceptable shrinkage and near maximum bending effect are obtainable.

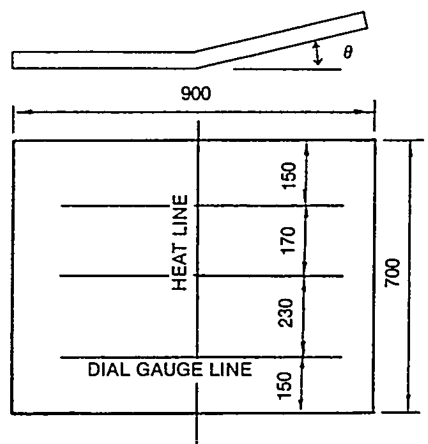


FIGURE 1-7: Method for determining bending or angular distortion (θ) obtained by line heating.

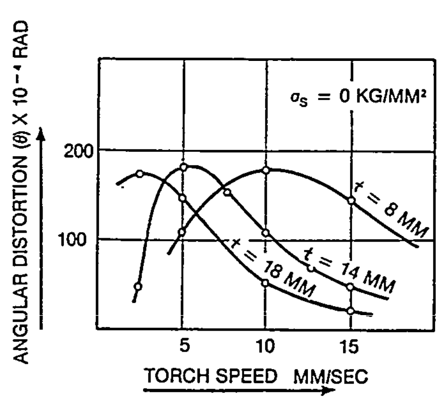


FIGURE 1-8: Angular distortion obtained by line heating with no initial stress. The curves, particularly for 14 mm plate thickness, are clearly related to the bending effect shown in *Figure 1-6.*

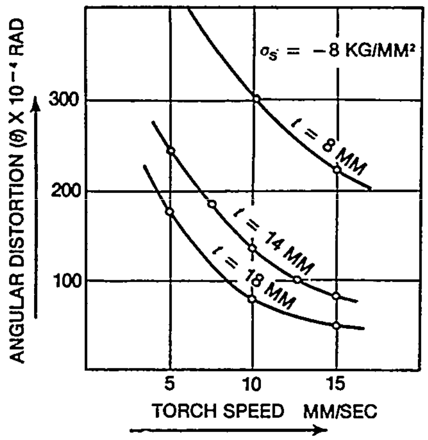


FIGURE 1-9: Angular distortion obtained by applying stress before line heating, is remarkably increased.

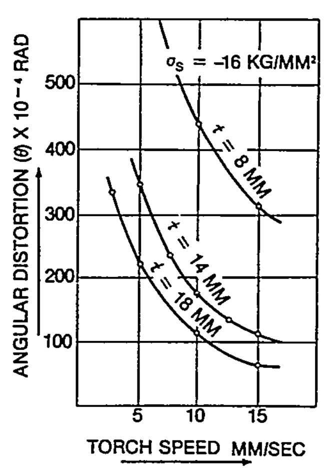


FIGURE 1-10: Greater initial stress as compared to that for *Figure 1-9*, further increases the angular distortion obtained by line heating.

Pertinent dimensions and orientations for this experiment were as illustrated in *Figure 1-7.* Certain factors were fixed as follows:

Ž travel speed (v): 10 mm/see
Ž initial stress (σ_S) : - 8 kg/mm²,
Ž acetylene pressure: 130 mmHg, and
Ž acetylene flow: 1,770 1/h @ O °C.

The factors to be varied were organized into two groups:

Group 1

Ž tip height from plate (H): 10, 13, 16 and 19 mm,
Ž oxygen pressure (P): 3.5 and 4.2 kg/mm², and
Ž plate thickness (t): 10, 14, 16 and 25 mm.

Group 2

- tip angle from plate: 900 and 1200,
- tip diameter (4): 3.05 and 3.35 mm,
- cooling-water flow (V_w): 2 and 3 l/rein, and
- cooling method (D_w): ring shower and hose stream.

The relationships pertaining to tip size, oxygen pressure and oxygen consumption are shown in *Figure 1-11.*

The experiment was carried out by combining the factors of Groups 1 and 2 based upon random choice probability.[1] The results identify tip height (H), oxygen pressure (P), plate thickness (t) and cooling method (D_w) as significant. A tip height of 16 mm was chosen as a standard and established as a strict requirement. This means that automated line-heating methods should feature "floating" torches that exactly follow existing curvature in a plate.

Oxygen Pressure	Oxygen Flow / tip diameter (ϕ)	
	3.35 mm (#40)	3.05 mm (#30)
3.5 kg/cm²	1550 l/h	1400 l/h
4.2 kg/cm²	1950 l/h	1750 l/h

FIGURE 1-11: Relationships pertaining to torch-tip size, oxygen pressure and oxygen consumption used to evaluate the effect of additional variables on bending by line heating.

Regarding oxygen pressure (P), only fluctuation in the order of 0.1 kg/cm² was determined to be permissible. Plate thickness (t) was incorporated in order to determine interaction. The results simply confirmed the influence of thickness as obtained from previously described experiments. A hose stream was found to be more effective and practical as a cooling method (D_w) than a shower ring.

There was no significance associated with the variations of other factors. The heating effect of the torch was essentially unchanged with varying tip angle. Therefore, tip angle to permit observation is permissible. As to tip diameter (ø), there was no difference in thermal effect when acetylene flow was kept constant. Thus, some tip wear is acceptable provided acetylene flow is controlled. A cooling-water flow (V_w) of 2 to 3 liters/minute was found to be enough.

[1] "An Experiment of Line Heating Design With the Table Orthogonal Array L_{32} (2^{31}) by T. Hashimoto and Y. Fujishiro, The Society of Naval Architects of Japan, November 1958.

1.7 Superimposed Line Heating

The pertinent geometry for an experiment which disclosed how superimposed heat lines and spacing of heat lines impact on bending effect is contained in *Figure 1-12.* As shown, it featured initial and final heating lines set at distance apart and an *n* number of intervening heating lines equally distant from each other and from the initial and final heating lines.

Figure 1-13 shows that when (= 0, i.e., when subsequent heat passes were on the same line, the bending effect diminished with each successive pass. *Figure 1-14* shows that when (was greater than 30 mm, there was no reduction in the bending effect of up to each of four subsequent passes.

1.8 Metallurgical Considerations

In general, when material is worked either hot or cold it is somewhat affected. An experiment was conducted which identified the resulting change in both material structure and mechanical properties due *to* line heating. The objective was to clearly identify safe heating limits.

The experiment, reported in 1961, included equivalent cold bending as a basis for comparison. It also included line heating to further form material that had been cold worked. The results established that line heating can be practiced just as safely as cold working.

Another such experiment measured the maximum temperature during line heating of a steel plate at 700°C when water cooled and at 800°C when permitted to cool naturally[3]. These were believed to be extreme because efficient bending was already being performed with lower temperatures. Even when heating to 800°C most but not all parts of the material did not exceed the A_1 transformation point[4]. Therefore, some brittle information which limits the extent of application was inevitable.

The experiment addressed brittle transition using Charpy impact tests. Interpretation of the curves showing relationships between impact value, temperature and distance from the heating lines indicated that controlled heating:

Ž is equivalent to cold bending in its affect on material quality,
Ž causes less degree of brittleness than welding, and
Ž has no appreciable affect on metallurgical structure.

Thus, compared to the other processes needed for fabricating parts, for assembling sub-blocks and blocks, and for erection, line heating is less harmful to material. Note should be made that line heating is quite different from red-hot heating usually applied for removal of extreme distortion such as dents and creases. Line heating, because it is carefully controlled, does not abnormally harden material.

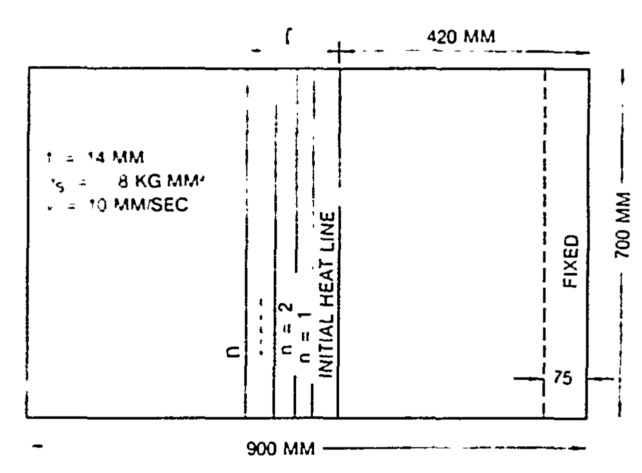


FIGURE 1-12: Method for determing the effect of superimposing and spacing heat lines.

The experiment continued by addressing the original properties of a steel plate and then its properties following successive working stages, i.e., rolling, cold bending and line heating. The results showed that line heating superimposed on cold-formed steel plate did not adversely affect mechanical properties. Instead, they were nominally improved. An additional experiment showed that line heating has the same affect on notch sensitivity of a steel plate as cold bending to an equal degree.

Factors such as heat source, heating method and cooling rate for line heating are similar to those for welding except that for line heating, temperatures are kept well below the A, transformation point, if a material is maintained heated for some time molecular change and grain growth may occur. There could be some metallurgical transformation dependent upon cooling rates. Therefore, in a practical application of line heating both heating and cooling are completed within a very short period. There is little time permitted for molecular change and grain growth. When properly controlled, no crystal-structure transformation can be detected even with a metalographic microscope.

1.9 Approvals

Line heating has been approved by the American Bureau of Shipping, Lloyd's Register and other classification societies as a proper method for bending ships' plates and other members. Line heating has been applied to virtually all kinds of steels and even to aluminum. However, there are certain requirements such as temperature limitations and the substitution of air cooling for water cooling which particularly apply to higher-strength steels and which vary with plate thicknesses. Thus, shipbuilders have to obtain approvals of line heating procedures from classification societies just as they do for welding procedures.

[3] "Plate Bending by Line Heating Method" a pamphlet by Ishikawajima-Harima Heavy Industries Co., Ltd., Tokyo, November 1973.

[4] In metallurgy A_1 is the Lower Transition Temperature and for low-carbon or mild steel it is 723 °C. At room temperature mild steel ordinarily consists of ferrite (∝ iron) and pearlite. On heating through A_1, the steel remains solid but these constituents begin to dissolve in each other in order to form austinite (γ iron) which has a different crystal-structure. In other words, a molecular change occurs in solid steel thus heated.

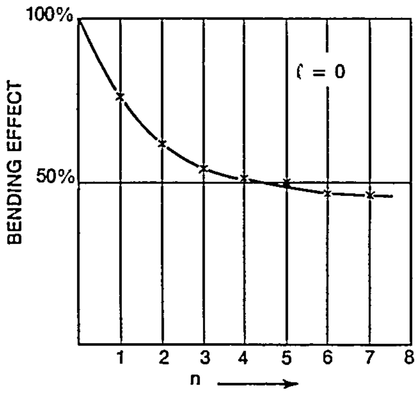


FIGURE 1-13: When ℓ = 0, i.e., when heat was superimposed on the same line, there was an appreciable drop in bending effect over the first four heat passes.

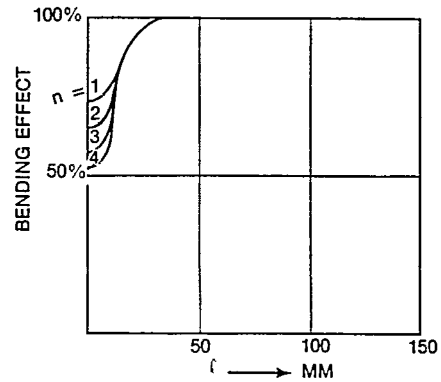


FIGURE 1-14: When ℓ was greater than 30 mm, there was no reduction in bending effect caused by up to four subsequent passes.

Approvals for higher-strength steels are known to exist **since as** early as 1969, e.g., “From results of hardness and impact tests it appears that the method of line heating to 650°C and watercooling is satisfactory and can be approved for thicknesses up to 12.7 mm for AH, 25.0 mm for BH, and 30.0 mm for CH and EH. However, because of the variables encountered in normal shipyard procedures, it is believed that the maximum permissible temperature, as measured by means of ‘Tempilsticks’, should be limited to 600°C.”

Pertinent supporting data is contained in a 1974 investigation to evaluate the effect of *flame straightening* on the mechanical properties of quenched-and-tempered steel. With heating limited to 565°C and water cooling, considerable straightening was achieved while there was no significant reduction in material strength or toughness.[6]

Since the foregoing history, significant progress has been made in perfecting line-heating methods. Temperature limits in effect during 1981 in a shipyard abroad which regularly employs line heating, are tabulated in *Figure 1-15.*

Kind of Steel	Maximum permissible heating temperature	Maximum temperature for commencing water cooling	Remarks
Mild steel	900°C	850°C	Air cooling and water cooling
High-tensile steel	900°C 900°C 650°C	— 500°C 650°C	Air cooling Water cooling Water cooling

FIGURE 1-15: Temperature limitations used in a shipyard abroad which regularly employs line heating.

Confirmation that line heating is permitted on all American Bureau of Shipping (ABS) grades of steel and ABS recommended limitations as of January 1982 are included in Appendix A. The temperature limits provided therein for reference, per shipbuilding research performed in Japan, are:

“(l) The heating temperature can be raised up to 800 °C ~903°C in case of air-cooling after heating.

(2) The heating temperature must not exceed 600°C~650°C in case of water-cooling immediately after heating.

(3) The heating temperature can be raised up to 800 °C~900°C in case of water-cooling after a certain period of air-cooling, however, the starting temperature of water-cooling should be below 500°C.”

2.0 LOFTING

2.1 Impact of Statistical Control

Scientifically derived line-heating work processes for forming many curved parts came into being over two decades ago. By 1961 competitive shipbuilders generally formed plates to rough shapes with presses or rollers and finished them with line heating. At that time the use of semi-automatically-operated multiple torches was already being considered as an alternative practice.

Although curved parts were being produced more accurately because of line heating, the advent of statistical-control techniques identified them as a continuing impediment to further improving productivity. Curved parts still required numerous dogs, clips, wedges, jacks, etc. to force them into place. Such fitting created locked-in stresses which were causing troublesome distortion after welding.

Analysis of the statistical-control charts maintained at each bending work station indicated that all processes were performing normally.[1] People and facilities were already doing their best. Thus, management concentrated on changing the system and soon discovered that workers did not have suitable means for determining the curvature achieved. In response to this identified problem, sets of sight-line templates were developed as means for maintaining a three-dimensioned inverse curve in space for each part to be formed. A worker then achieved specified curvature by systematically line heating until the inverse curve was transformed into a straight line; see *Figure 2-1.*

Making clear to everyone concerned how work processes are performing is a basic statistical-control measure. Such knowledge encourages spontaneous inputs from workers about how to further improve work processes.[2] Thus, the introduction of sight-line templates caused an explosion of ideas. Practical devices for holding templates in position were soon developed. Computer routines and formats were composed for quickly and accurately preparing sets of sight-line data or patterns on Mylar sheets. As shown in *Figure 2-2,* adjustable templates replaced those made of wood. Their use was extended for curving and twisting longitudinal; see *Figure 2-3.* Semiautomatic operation of multiple torches, *Figure 2-4, was* initiated and made possible curving plates of greater widths and lengths.

The overriding objective was to more accurately form curved parts in order to avoid distortion. However there were other significant benefits such as enhanced safety and a reduction in the overall man-hour costs to one third of those previously needed, e.g.:

- bending was simplified as compared to conventional rolling and pressing so that much could be performed with less-skilled workers,
- available skilled workers concentrated on complex parts such as stem plates,
- much work was eliminated such as that associated with traditional fitting devices such as dogs, pads, yokes and clips, and
- rework for chipping free fitting devices and subsequent filling and grinding to restore surfaces was greatly reduced.

[1]Statistical control is the analytical management technique for manufacturing taught by Dr. W. Edwards Deming, the statistician who is known as the father of productivity in Japan. In shipbuilding, statistical logic is proven to be very effective for fabrication and assembly work; see "Process Analysis Via Accuracy Control - February 1982" by S. Nakanishi and L.D. Chirillo for the National Shipbuilding Research Program.

[2]Per Dr. W. Edwards Deming, statistical methods distinguish faults of management's system (85%) from problems caused by workers or machines (15%). When workers are not blamed for problems they can do nothing about, a climate exists for spontaneous quality circles. According to Mr. Joji Arai of the Japanese Productivity Center, in Japan where they are most effective ". . . quality circles grew out of statistical techniques first introduced in the 1950s ". INC., August 1982, p. 100.

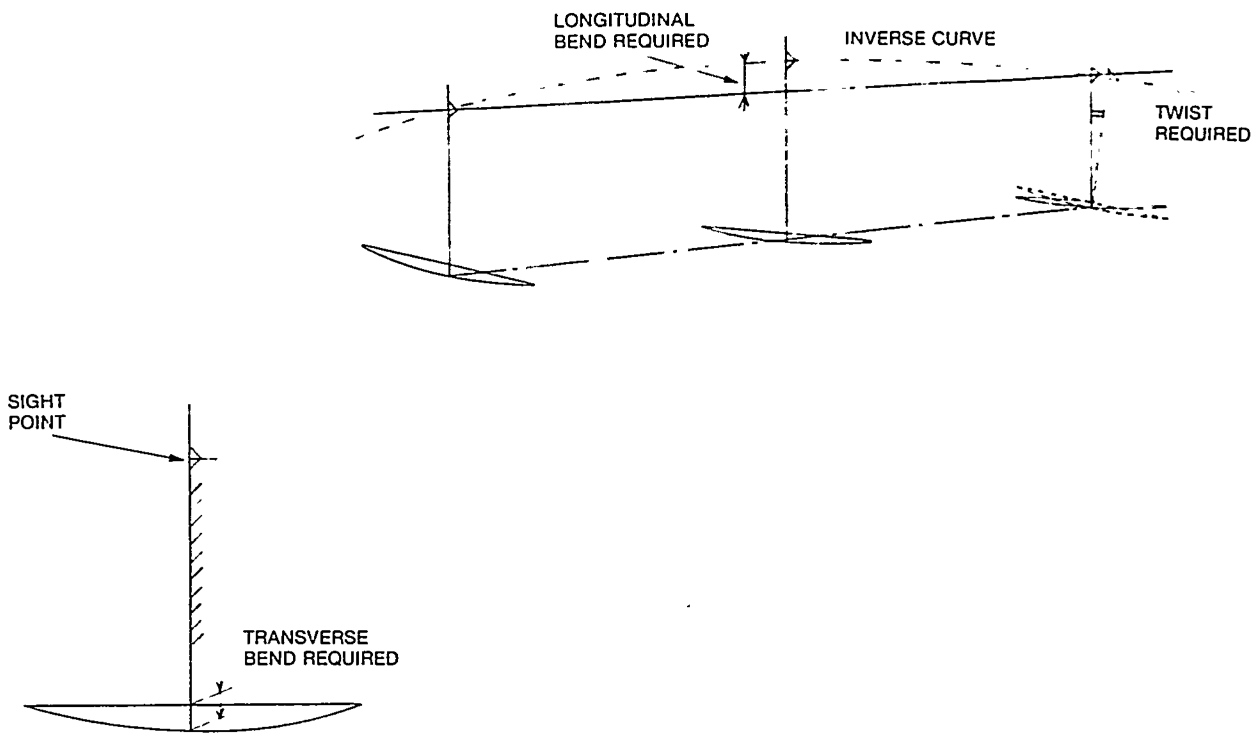
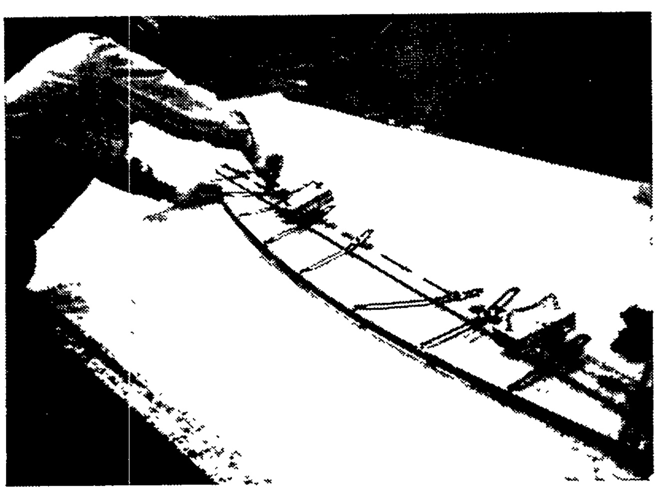


FIGURE 2-1: Sight-line templates maintain a three-dimensional inverse curve in space.



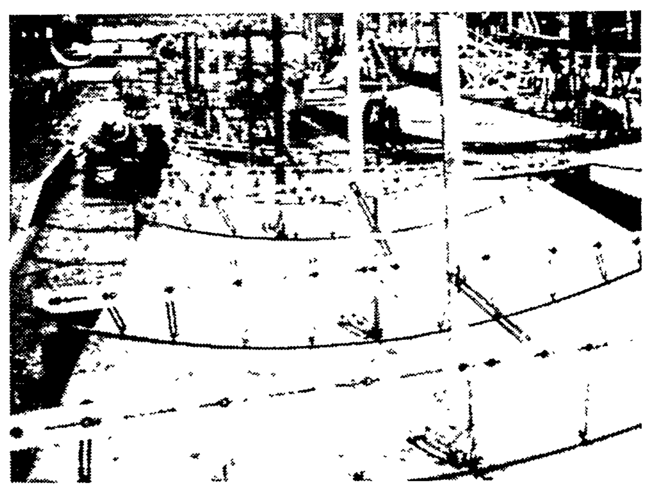


FIGURE 2-2: Adjustable templates are set in the shop and are reusable. Details of their construction, including those for wood templates and for template holders are in Appendix B.

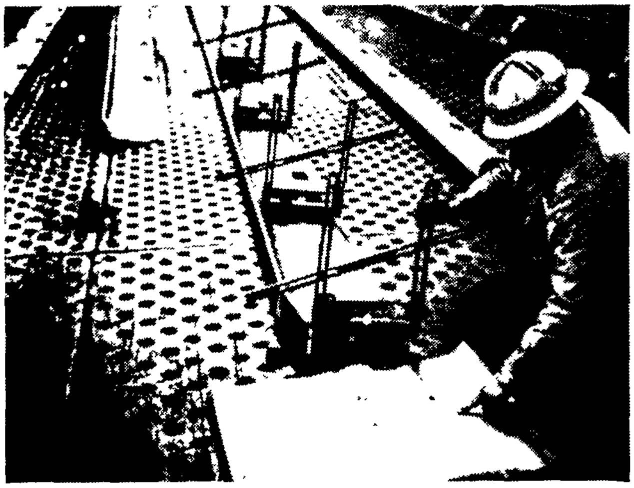


FIGURE 2-3: Adjustable sight-line templates are also used for twisting longitudinals.

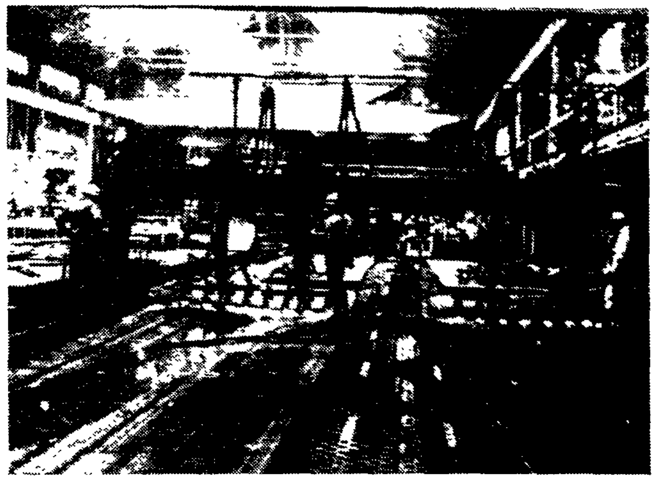


FIGURE 2-4: Semiautomatic operation of multiple torches facilitates curving plates of greater widths and lengths. Symmetrical plates, for port and starboard, are curved simultaneously.

2.2 Work Instructions

Work instructions prepared by a loft are crucial for effective performances by line heating workers. When calculations are performed for developing a plate, the locations of the following lines are determined and included in the work instructions for marking:

- frame lines,
- sight baseline, and sometimes
- roll axis,

The frame lines and sight baseline are necessary for positioning templates as shown in *Figure 2-5.* The sight baseline serves to fit each template at a prescribed point of tangency and at a specified angle relative to the plate surface. The roll axis is required for orienting heating lines and for mechanical bending when both processes are used in combination. Although computer-aided lofting is common, not all programs define a roll axis. In such cases methods which employ the templates are used.

In addition to part-identification data, the following work instructions are annotated on each template of a set as shown in *Figure 2-6*

- position relative to plate length,
- location relative to sight baseline,
- angle of the template holder,
- location of the "up" seam,
- location of the "down" seam, and
- a clearly defined sight point.

Positions relative to each plate include "fore butt", certain frame lines and' 'aft butt". Dependent on plate lengths, three to six templates are usually required. A practical standard for the numbers and positions of templates is shown in *Figure 2-7.*

The angle of the template holder is relative to the mean angle of the curved plate along the base of the holder. Care is needed in setting the angle of each template holder, particularly for butt templates. An error in the setting of such angles shifts the sight line and causes inaccurate longitudinal curvature, see *Figure 2-8.*

The work instructions for setting adjustable templates are organized to be as simple as possible. The different curvatures required justify different formats as shown in *Figures 2-9, 2-10* and *2-11.* The heights and widths of the formats are sometimes limited by the sizes of numerical control (N/C) drafting tables.

2.3 Sight-line Development

Methods for sight-line development are illustrated in *Figures 2-12* through *2-24.* Each example employs a body plan and a frame number sequence from aft to forward. *Figure 2-13* illustrates extra effort in the loft to incline the sight line so that it is more conveniently oriented for a worker of average height. *Figures 2-14, 2-17* and 2-18 show how sight lines are shifted in order to further simplify line heating work by nominal additional work in the loft. An inverse curve for bending and sight-line development for twisting a longitudinal are shown in *Figures 2-25* and 2-26 respectively.

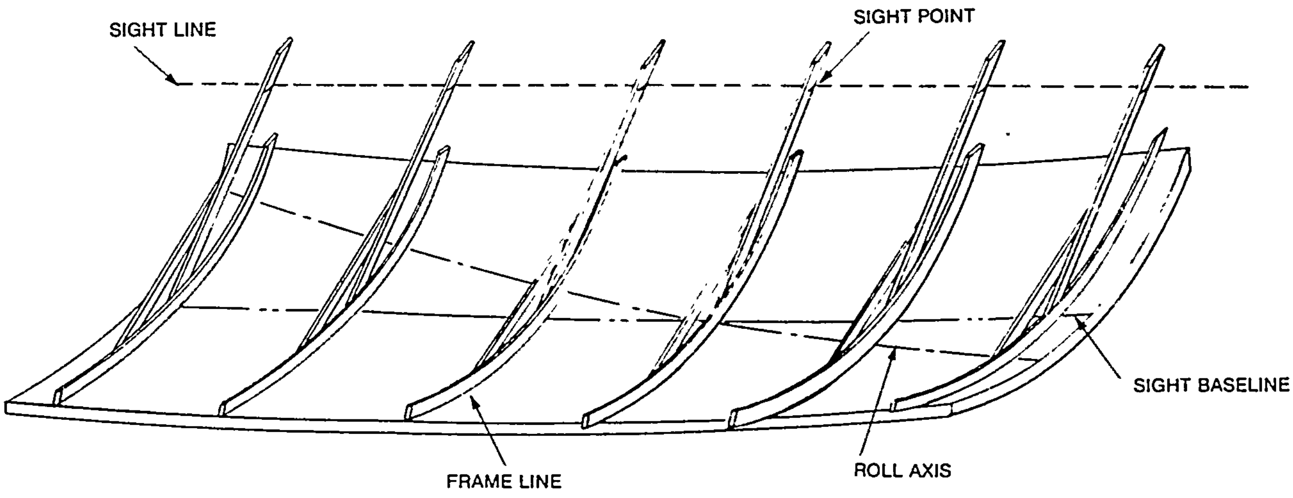


FIGURE 2-5: The frame lines and sight baseline are necessary for positioning templates. Each template is placed across the sight baseline at a prescribed point of tangency and set at a specific angle relative to the plate surface.

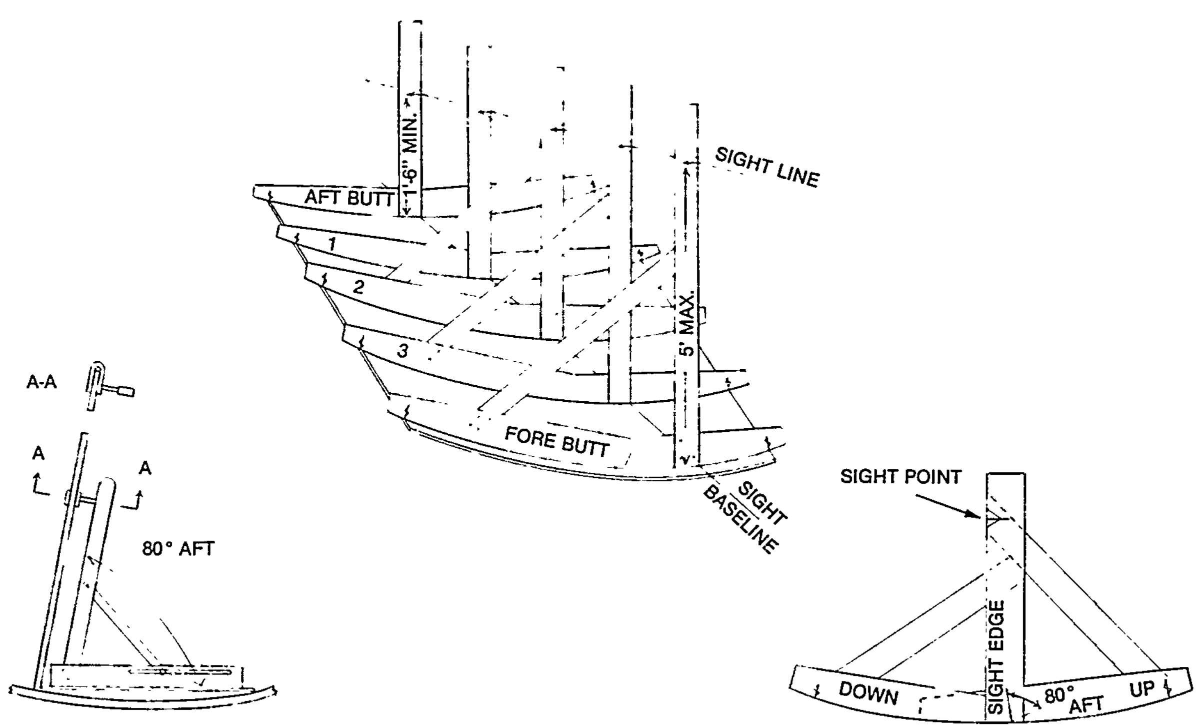


FIGURE 2-6: The base of the template holder is located near and parallel to the sight baseline. The angle specified is relative to the mean angle of the curved part of the plate on which the holder rests. Sight points are marked on both sides of the templates because each set of templates is used for a pair of symmetrical plates. In a shipyard where line-heating techniques are very advanced, the sight edges appear on the right for port-side plates and on the left for starboard-side plates. As shown, the sight line is inclined to facilitate observation by workers. A tall person stands a bit further away.

NUMBER OF FRAME LINES IN A PLATE	STANDARD QUANTITY OF TEMPLATES	STANDARD TEMPLATE POSITIONS
3	3	AFT BUTT - 2 - FORE BUTT
4	4	AFT BUTT - 2 - 3 - FORE BUTT
5	4	AFT BUTT - 2 - 4 - FORE BUTT
6	4	AFT BUTT - 2 - 4 - FORE BUTT
7	4	AFT BUTT - 3 - 5 - FORE BUTT
8	5	AFT BUTT - 3 - 5 - 7 - FORE BUTT
9	5	AFT BUTT - 3 - 5 - 7 - FORE BUTT
10	5	AFT BUTT - 3 - 5 - 8 - FORE BUTT
11	5	AFT BUTT - 3 - 6 - 9 - FORE BUTT
12	6	AFT BUTT - 3 - 5 - 8 - 10 - FORE BUTT
13	6	AFT BUTT - 3 - 6 - 9 - 11 - FORE BUTT
14	6	AFT BUTT - 3 - 6 - 9 - 12 - FORE BUTT

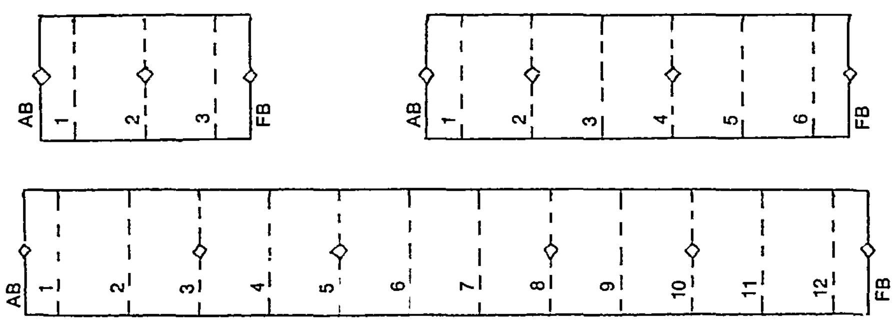


FIGURE 2-7: The quantities and positions of templates are standardized, as shown, relative to the numbers of frame lines represented. For relatively large rates of curvature, more templates are provided.

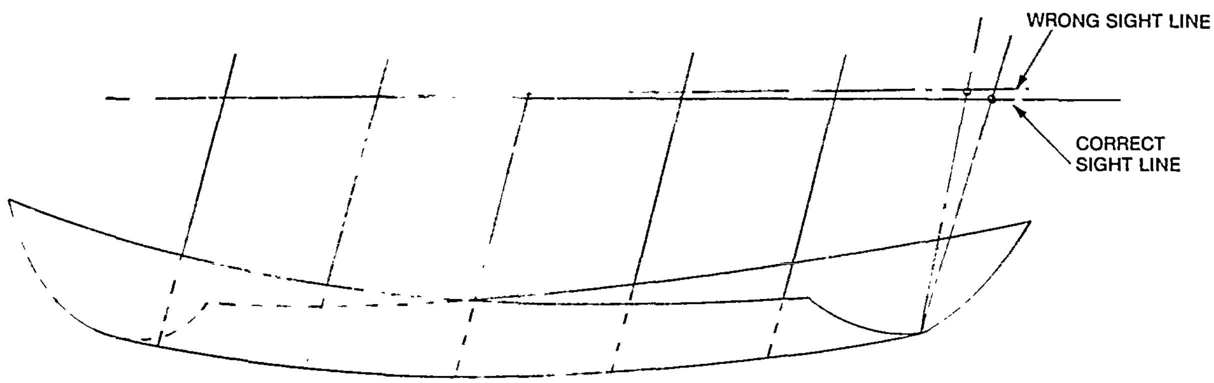


FIGURE 2-8: Errors in setting holder angles for butt templates are not readily apparent, shift the sight line and cause inaccurate longitudinal curvature.

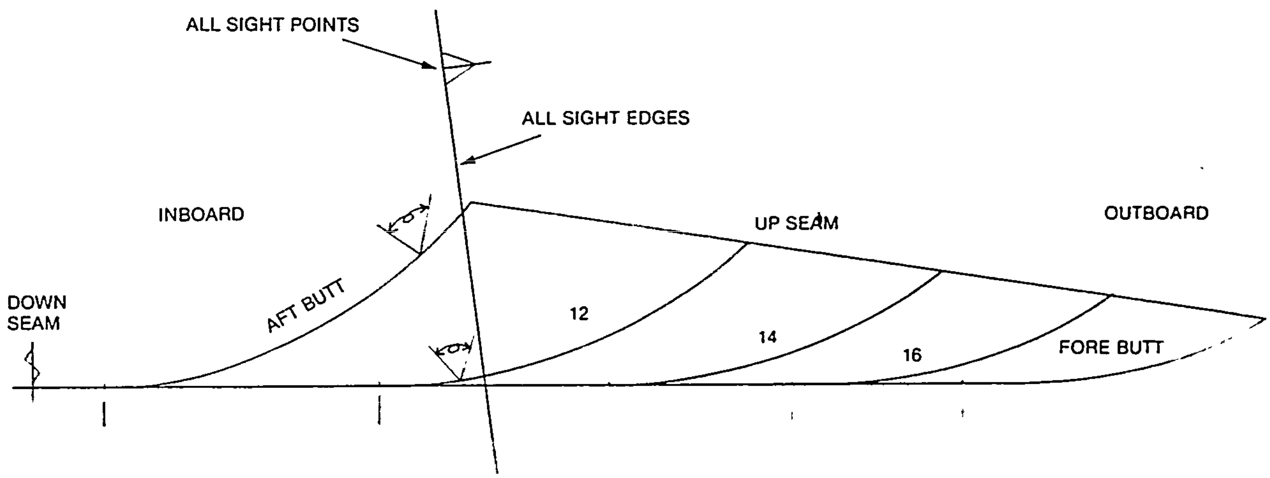


FIGURE 2-9: Pattern for a bottom plate defined on a body plan. A single line represents all sight edges and a single point represents all sight points for five different templates. The angles for the template holders are shown for the aft butt and for frame 12. When such angles are not specified, as for frame 14, frame 16 and the fore butt, the template holders are set at 90 degrees.

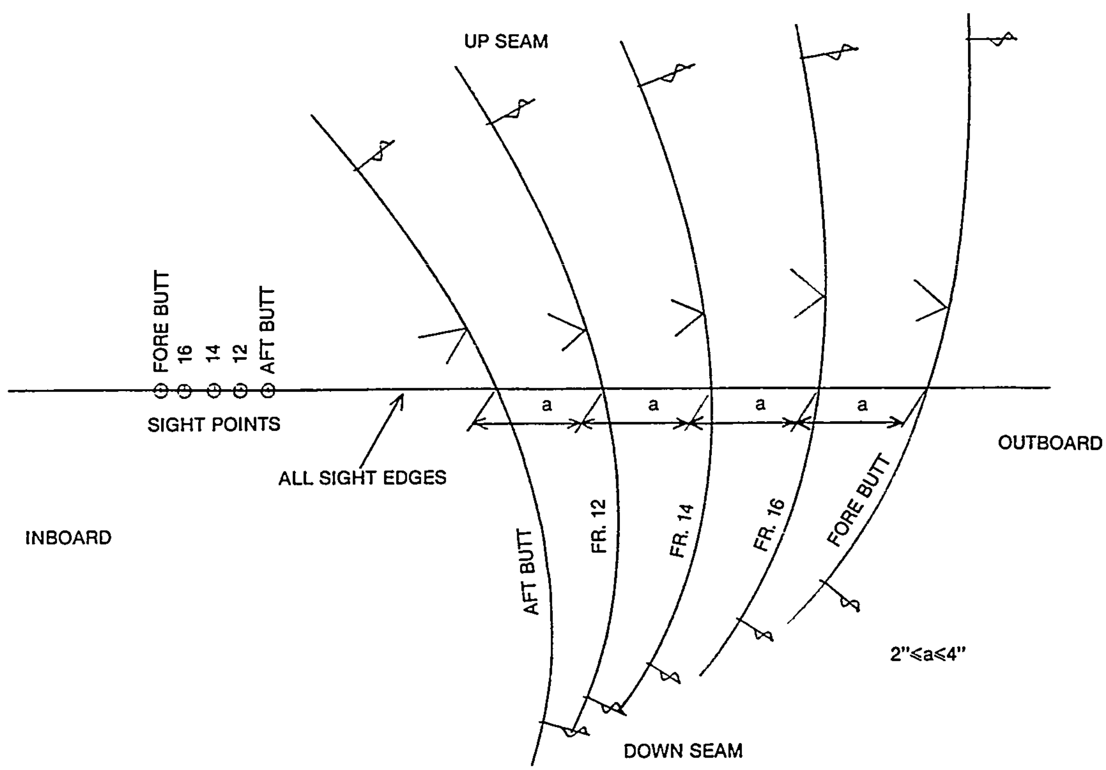


FIGURE 2-10: Pattern for a side shell or bilge plate. A single line represents the sight edges of all templates. The plate is not defined as a body plan because the curves are separated by some convenient distance, "a", in order to improve legibility. Thus, separate sight points are necessarily shown for each template.

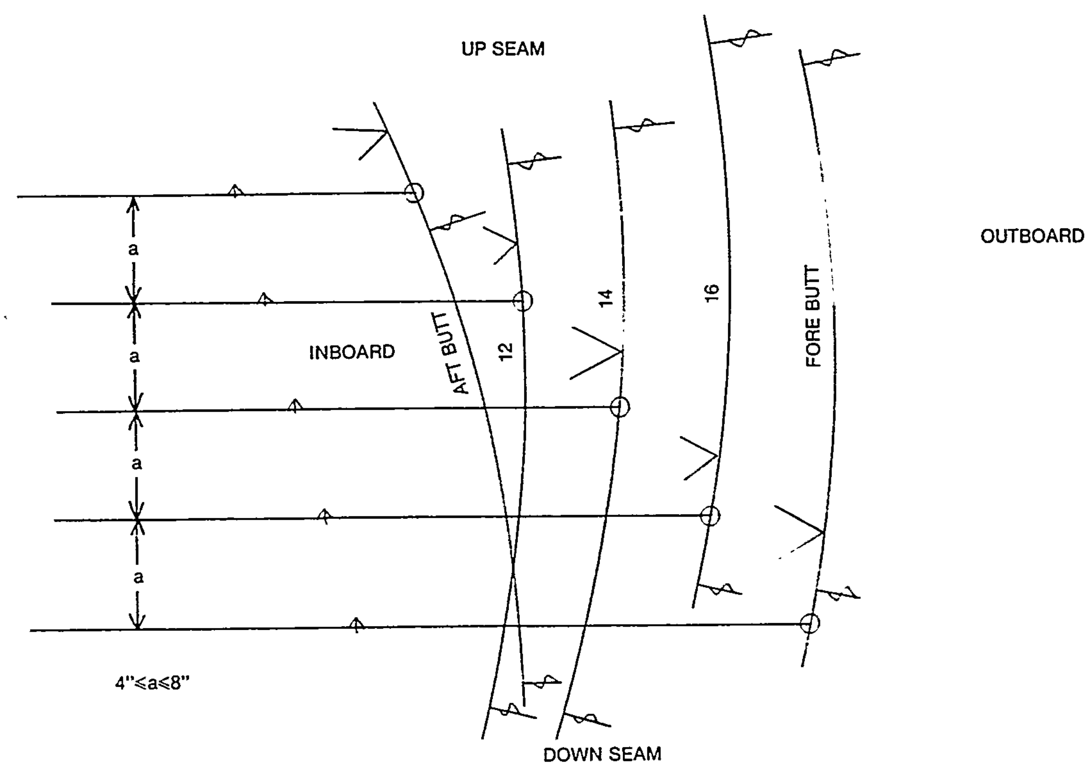
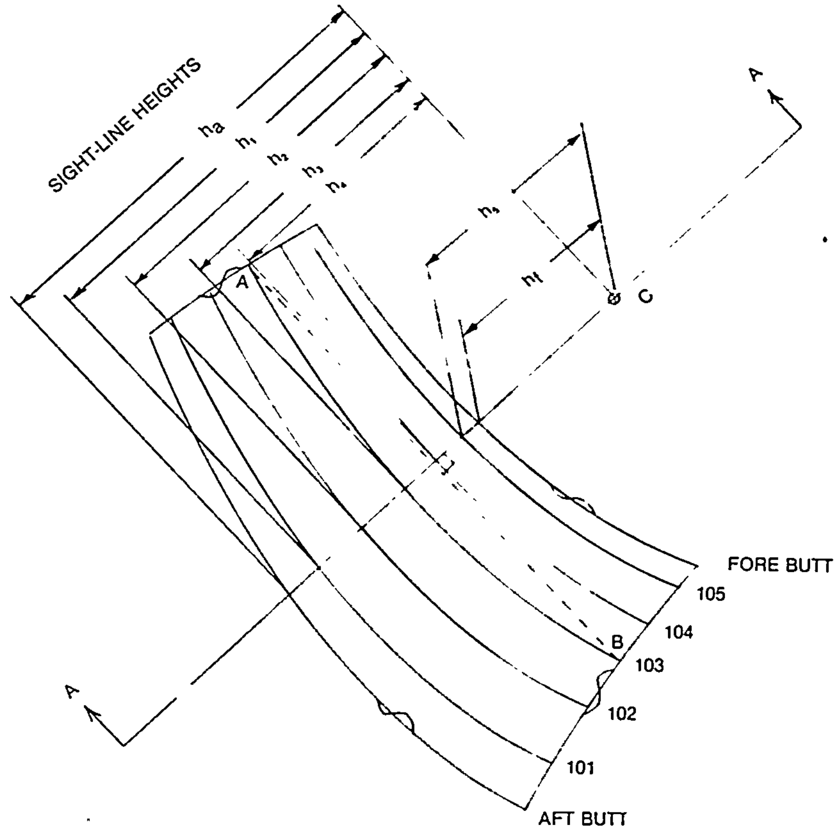


FIGURE 2-11: Pattern for a plate with twist. The plate is not defined as a body plan in order to improve legibility. Separate but parallel sight edges are employed.



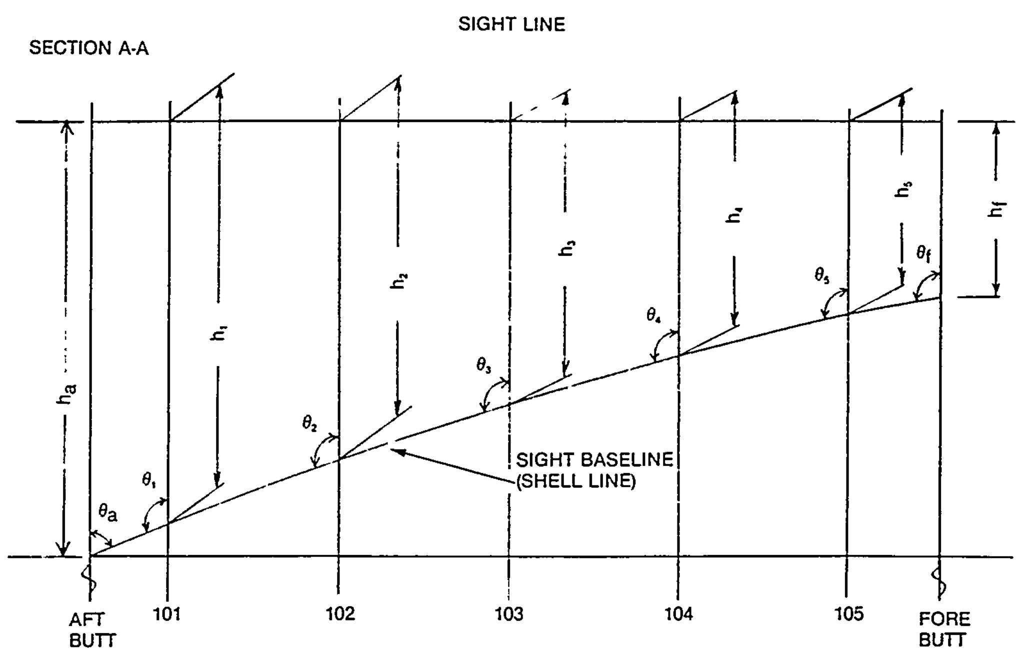
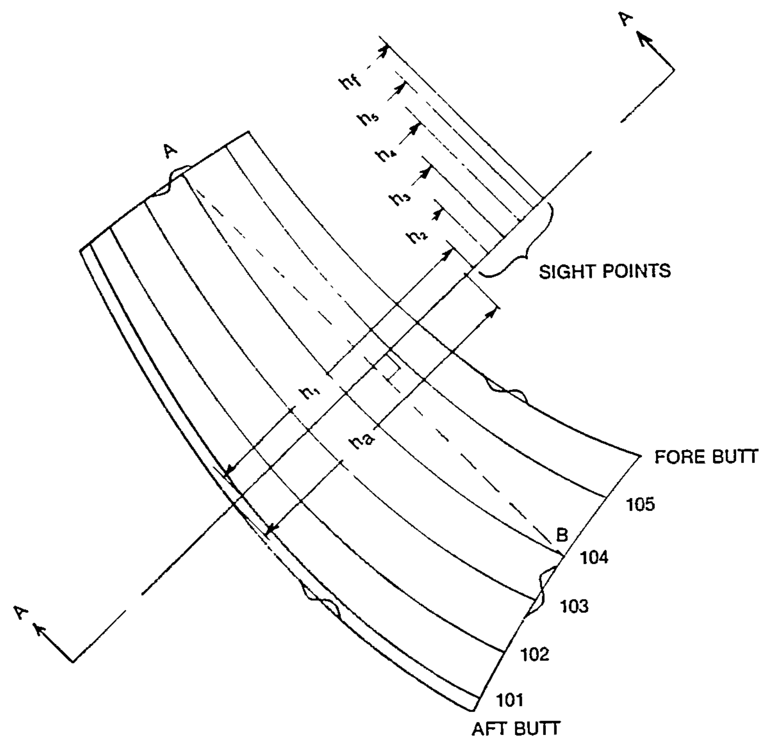


FIGURE 2-12: Sight-line development. The perpendicular bisector of the chord AB represents all sight edges. The arc AB is the middle frame line. Point C, which represents all sight points, was established so that h_a is equal to or less than 5 feet and h_f is equal to or greater than one foot. The angles for setting the template holders are derived from Section A-A. Angle θ_a is specified "forward" and all others are specified "aft" of their respective butt and frame lines.



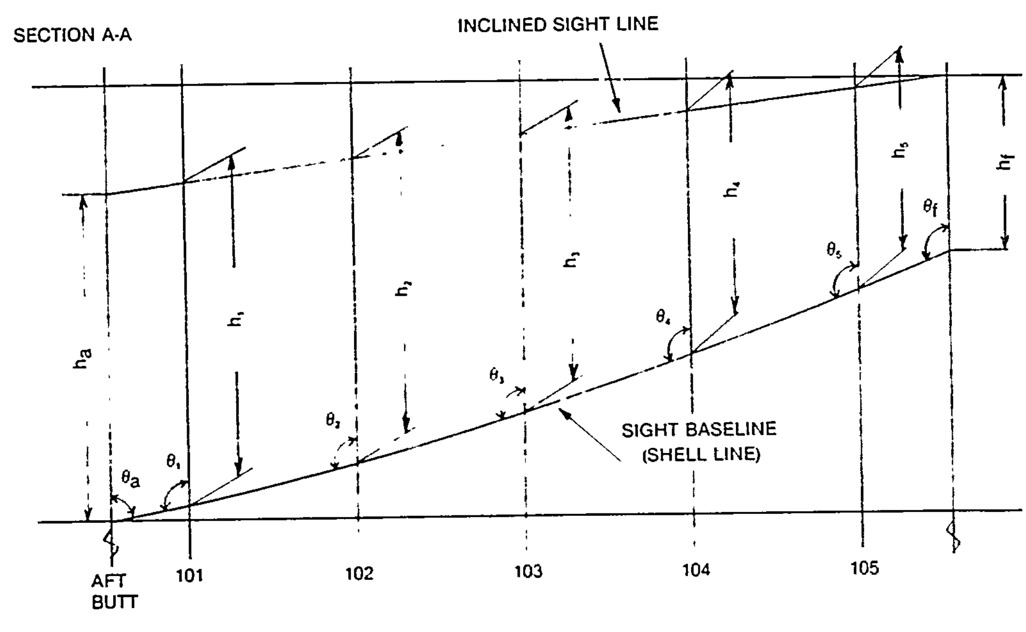


FIGURE 2-13: Inclined sight-line development. Inclining a sight line is sometimes necessary in order to facilitate observation by workers. Thus, additional calculations are performed in lofting as a means of further simplifying work. As in *Figure 2-12*, the perpendicular bisector of chord AB represents all sight edges. The sight line is inclined so that h_a is less than or equal to 5 feet and h_f is greater than or equal to one foot. Next, the positions of the remaining sight points are scaled from their respective frame lines in Section A-A.

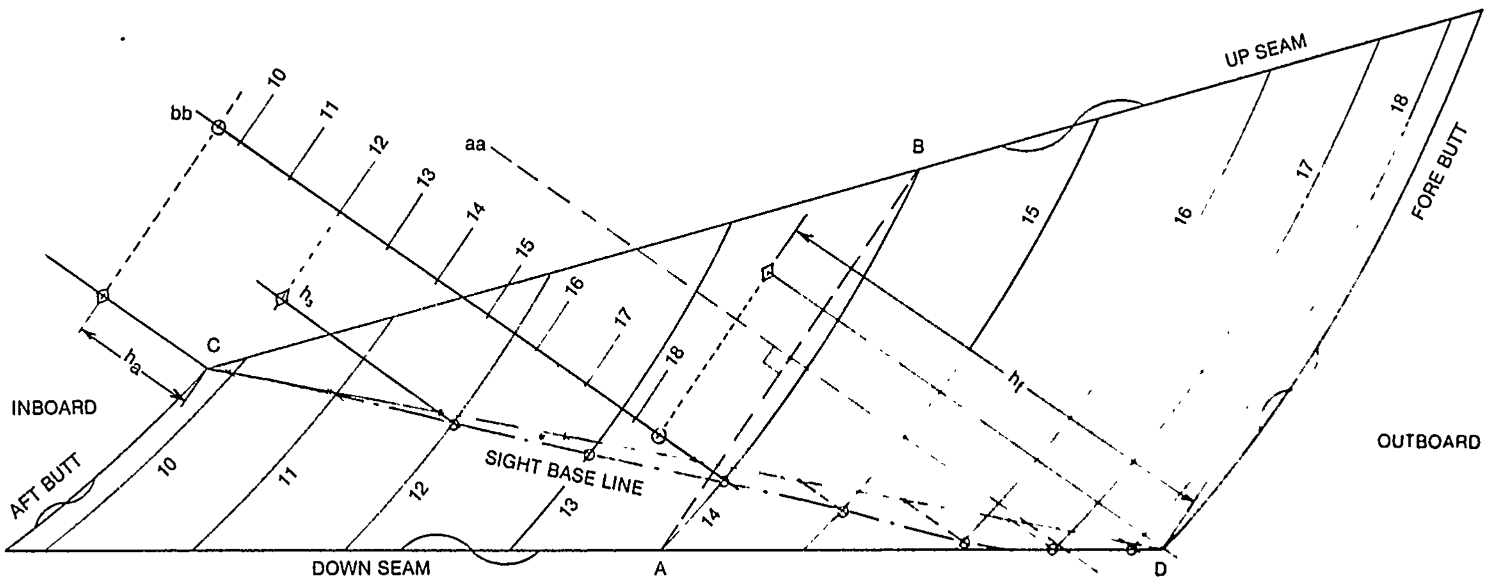


FIGURE 2-14: Translating a sight line when aa, the perpendicular bisector of AB, does not intersect a butt. CD is drawn through opposite corners of the plate and is subdivided proportionally according to frame spacing and the distances of butts from frames. Lines drawn through the division points on CD and parallel to aa, represent sight edges. Their intersections with their respective frame lines define the sight baseline. As shown, h_a and h_f are fixed at one foot and 5 feet respectively. These sight points are transferred to line bb which represents the sight edge for the mid-frame. The distance between the transferred points is divided proportionally according to frame spacing and the distances of frames from butts. As shown for h_i, the height of a specific sight point is obtained by translating from line bb to its respective sight edge.

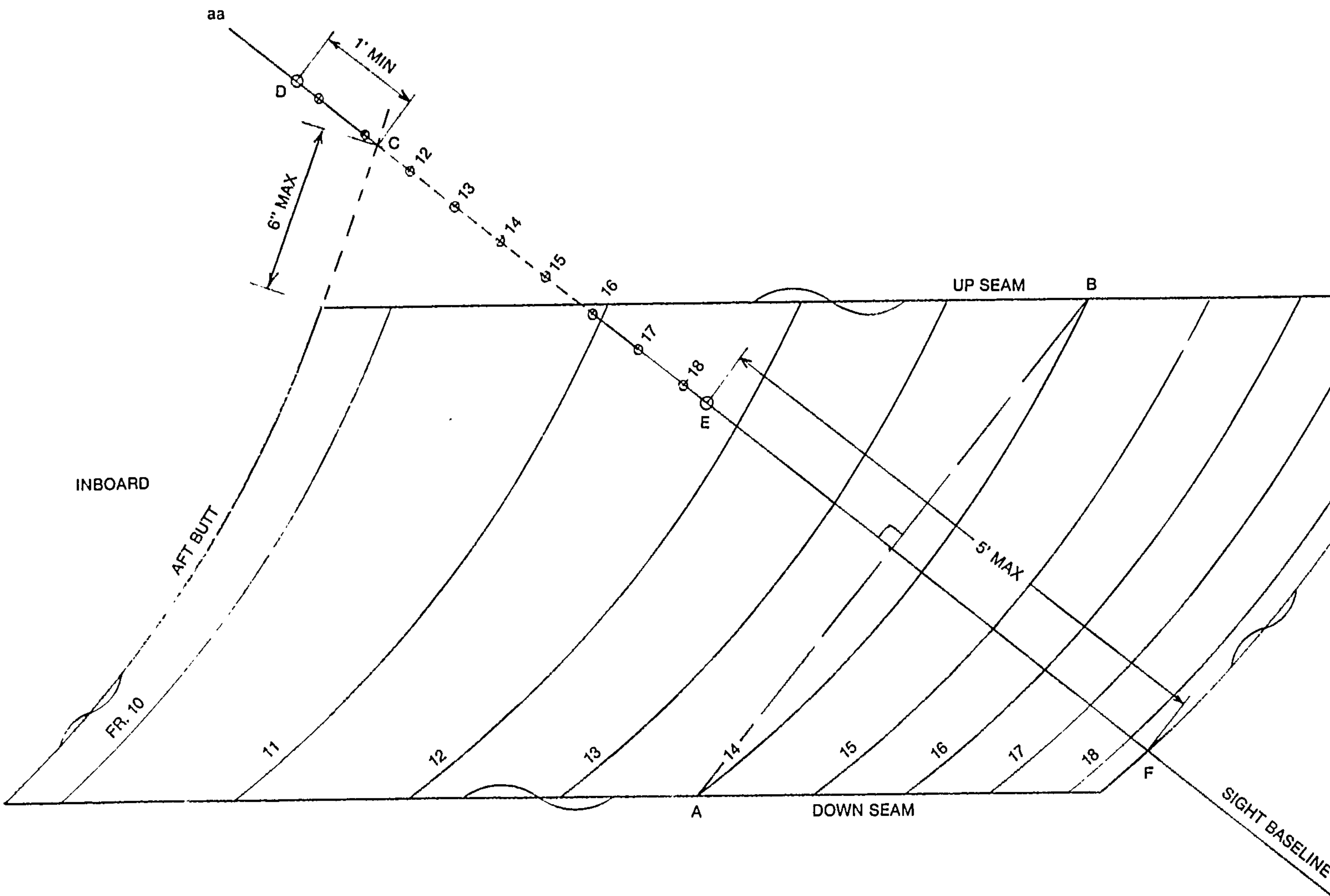


FIGURE 2-15: Simplified sight-line development when aa, the perpendicular bisector of AB fails to intersect a butt by 6 inches or less. As shown, the line representing the aft butt and line aa are extended in order to determine point C. Point D is located so that CD is greater than or equal to one foot. Point E is located so that EF is less than or equal to 5 feet. DE is divided proportionally according to frame spacing and distances of butts from frames in order to determine the heights of sight points corresponding to each frame line. Although this method is sometimes employed to relieve an excessive loft workload, transferring the sight line as described in *Figure 2-14* is more accurate and is preferred.

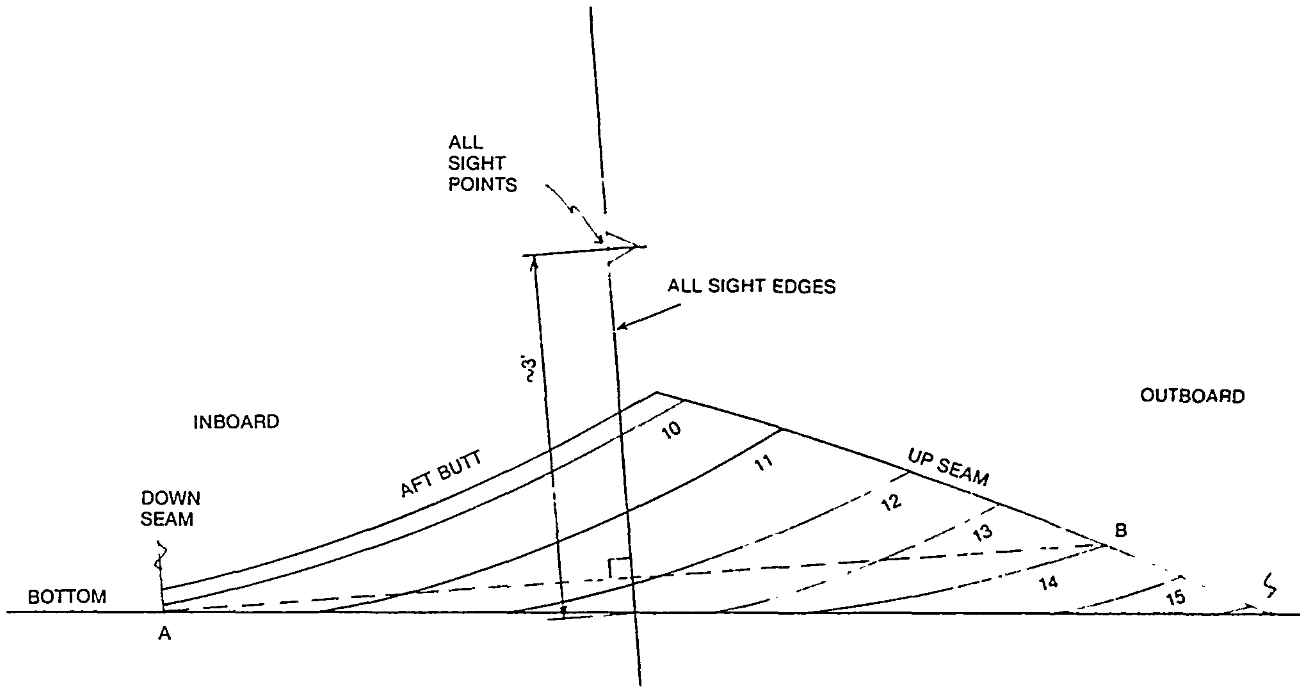


FIGURE 2-16: Sight-line development — bottom shell. The perpendicular bisects a chord that is for other than mid frame. The chord for frame 14 was selected because its perpendicular bisector is the first one away from mid frame which intersects the aft butt and because it is nearly vertical. Sight edges which are vertical or nearly vertical after bending, facilitate observation by line heating workers. In this example the chord for frame 14 is the best compromise.

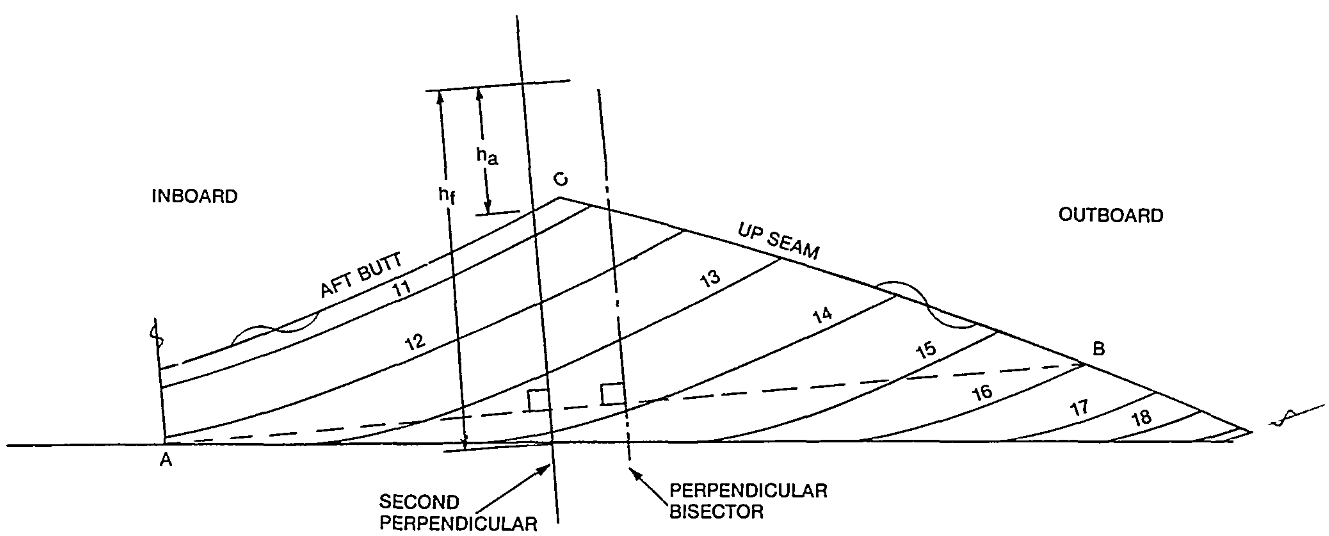


FIGURE 2-17: Sight-line development — bottom shell. The perpendicular bisector of the chord which is the best compromise fails to intersect the aft butt. *A second perpendicular is established which intersects the butt close to the corner C. If the corner is relatively high, h_a is fixed so that it is greater* than or equal to one foot and h_f is fixed so that it is less than or equal to 5 feet.

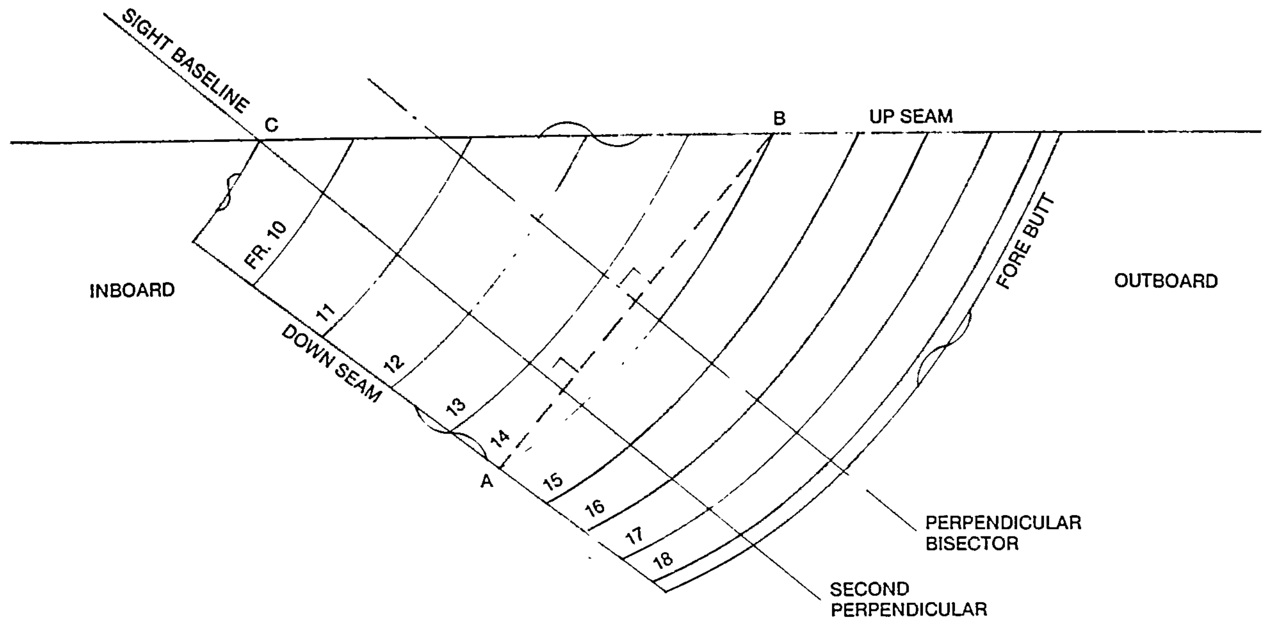


FIGURE 2-18: Sight-line development — bilge. The perpendicular bisector fails to intersect the aft butt. A second perpendicular is established so that it intersects the butt at or close to point C.

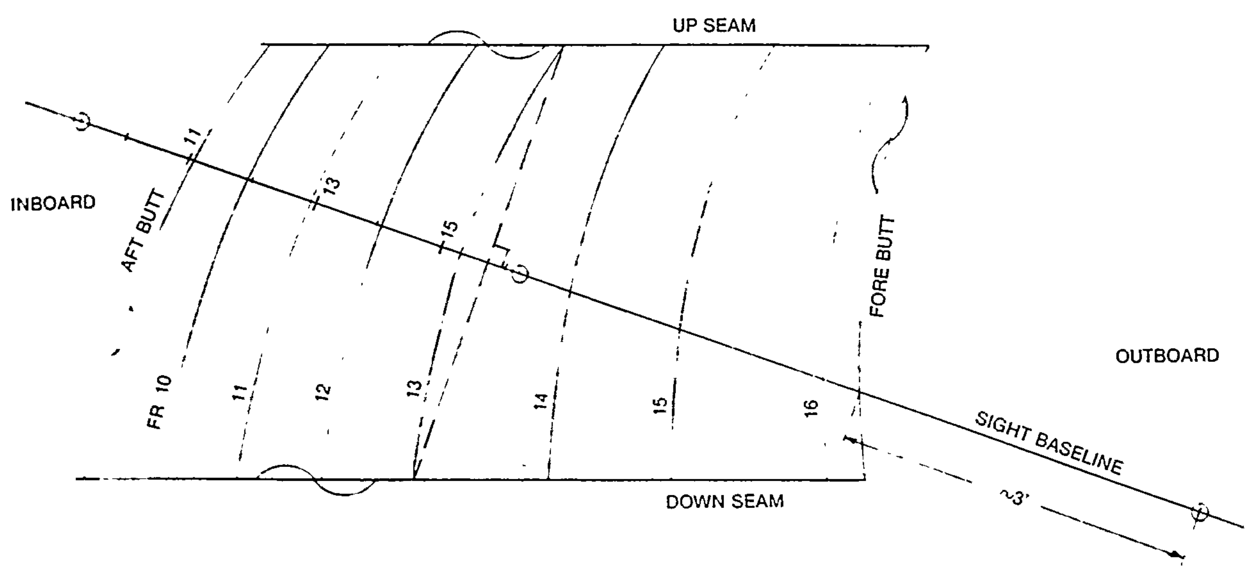


FIGURE 2-19: Sight-line develpment — saddle shell-plate only. The process is the same as those previously described with an exception. At least three additional templates are needed, at frames 11, 13 and 15, which allow for plate thickness. They are used for checking the curvature of the outside surface.

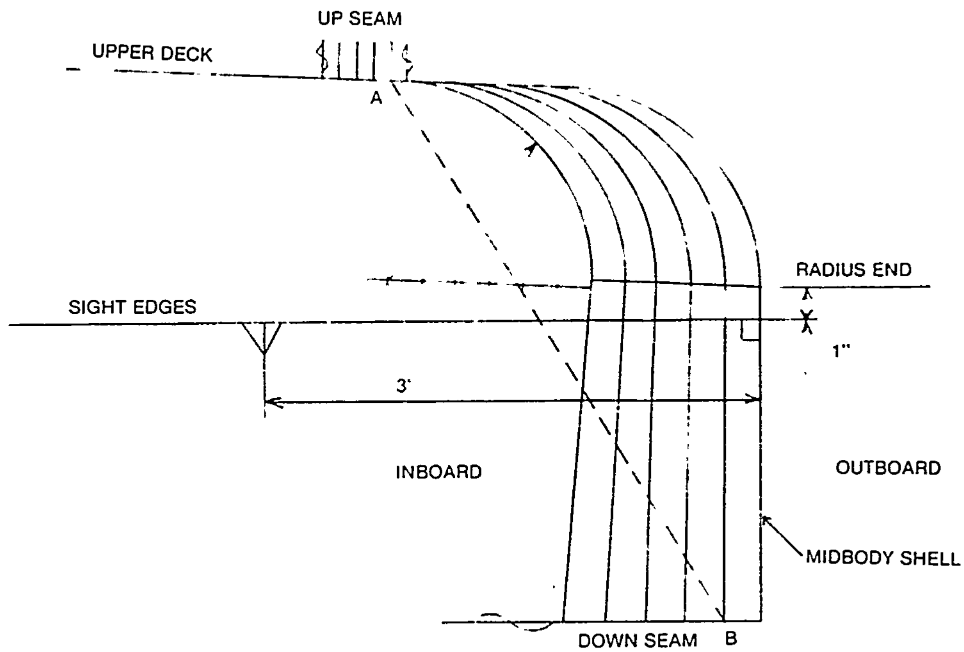


FIGURE 2-20: Sight-line development — gunwale plate only. In this special case, a perpendicular to a chord such as AB is not desired because the sight edges would not be vertical or nearly so as is best for workers. Thus, a line representing all sight edges is established one inch from radius end and perpendicular to the midbody shell. A point representing all sight points is fixed 3 feet from the midbody shell.

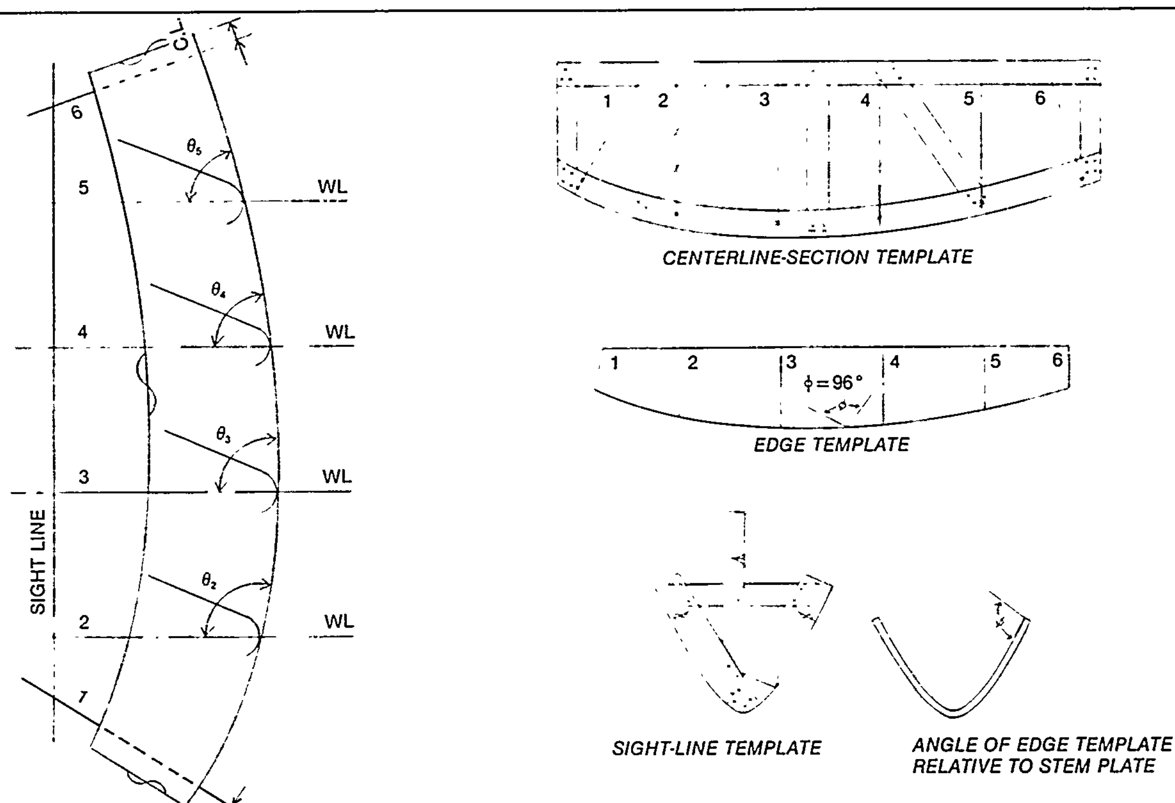


FIGURE 2-21: Sight-line development — convex-stem plate (65°$\leqslant\theta\leqslant$115°). When waterlines are relatively normal to the profile curvature of the stem, sight-line templates are prepared to correspond with each waterline section and with sections normal to curvature at the top and bottom. Special templates are prepared for the centerline section and edge as shown.

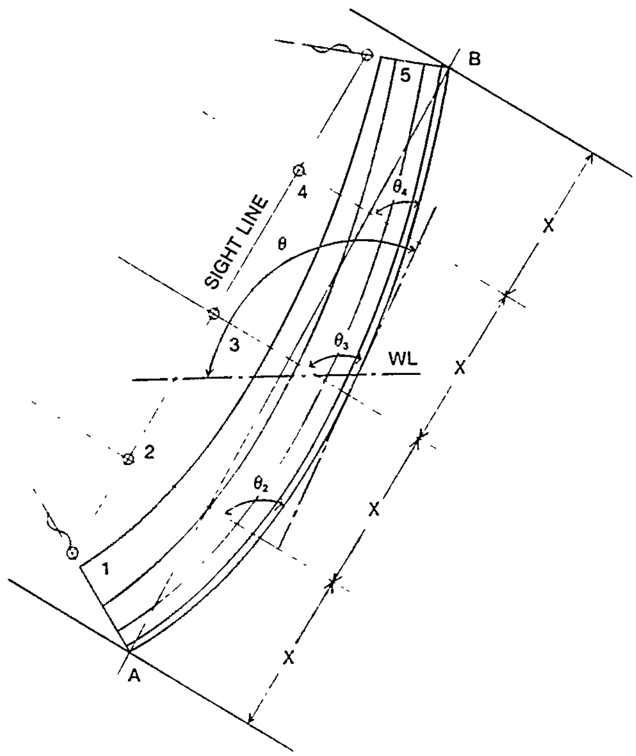


FIGURE 2-22: Sight-line development — convex-stem plate (65°>θ>115°). Chord AB is divided into equal parts so that 1' – 6"< x <2' – 6". At each division in this example, special sections (2, 3 and 4) are established perpendicular to the chord and end sections (1 and 5) are established normal to the profile curvature of the stem. The sight-line templates, the centerline-section template and the edge template are similar to those shown in *Figure 2-21.*

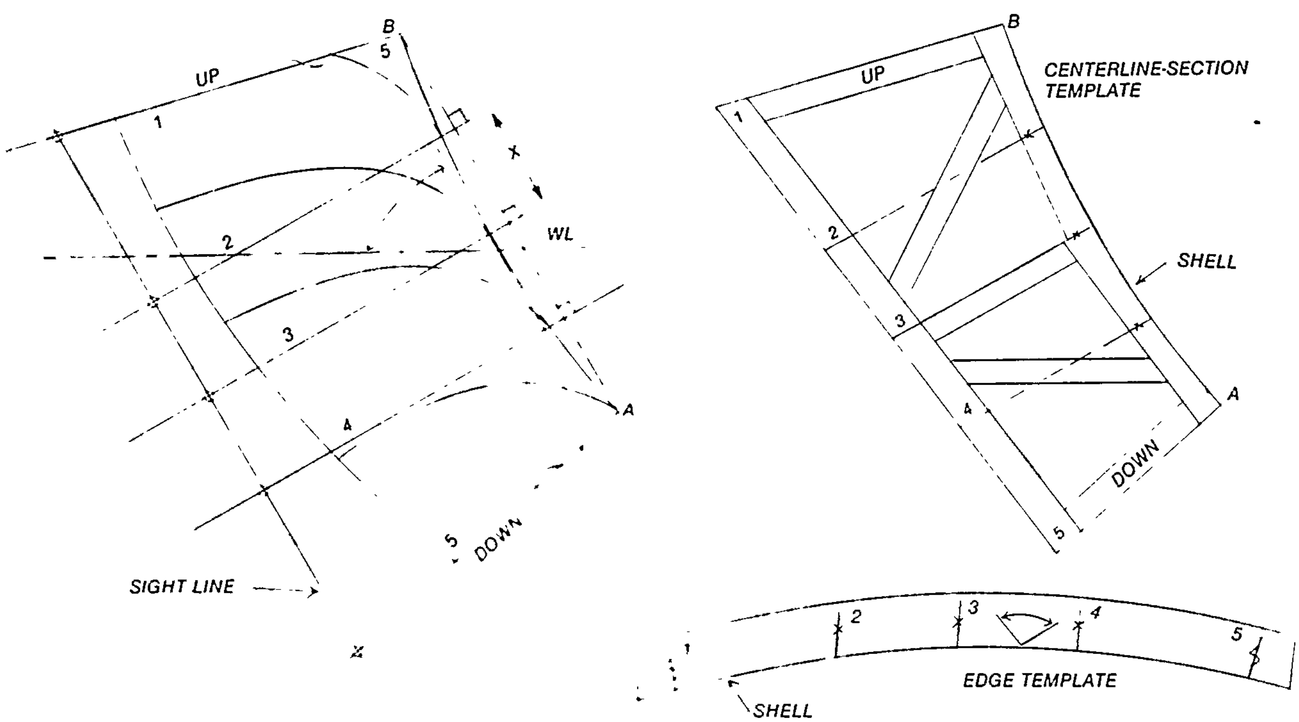


FIGURE 2-23: Sight-line development — concave-stem plate. When waterlines are relatively normal to the profile curvature of the stem (65°≤θ≤115°), sight-line templates correspond with each waterline section and with the sections normal to the stem curvature at the top and bottom just as in *Figure 2-21* for a convex-stem plate. When waterlines are not relatively normal to the profile curvature (65°>θ>115°), chord AB is divided into equal parts and thereafter the procedure is the same as for *Figure 2-22.* The sight-line templates are similar to those shown in *Figure 2-21.*

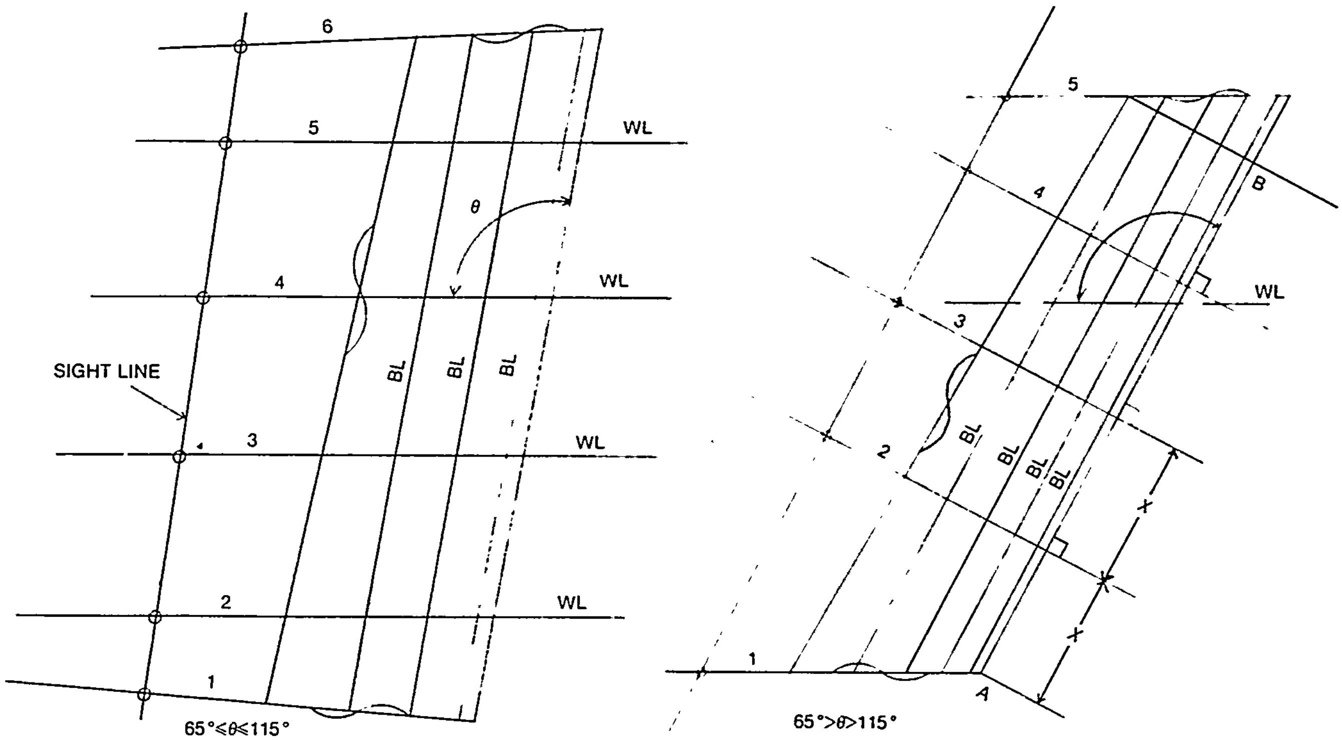


FIGURE 2-24: Sight-line development — fashion stem plate. As shown on the left, when waterlines and lines representing ends are relatively normal to the stem profile, sight-line templates are prepared for each 2-foot pitch waterline section and each end section. As shown on the right, when relative normalcy does not exist, the line AB is divided equally so that 1' – 6"< x <2' – 6". Sight-line templates are prepared to correspond with the perpendiculars to the stem (2, 3 and 4) and for the end sections (1 and 5). Centerline section and edge templates are prepared for both cases.

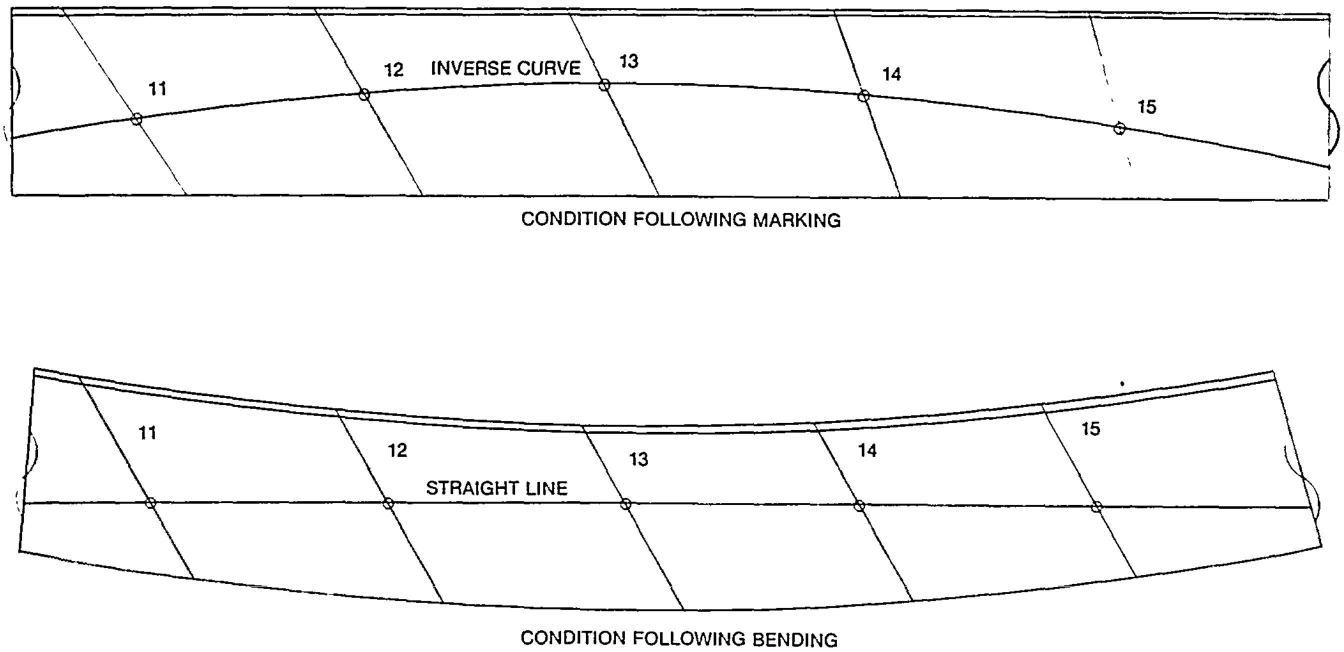


FIGURE 2-25: An inverse curve is marked on a straight longitudinal in such a way that when prescribed bending is performed, the curve is transformed into a straight line. A taut string is used to verify that the line is straight. Thus, templates are not required and checking for proper curvature is very easy for a worker. In some shipyards, longitudinal lengths are cut neat, i.e., *no extra material is* allowed for a bending machine to grasp the ends. After as much bending as possible is performed by machine, triangle heating, a variation of line heating, is used to bend the ends.

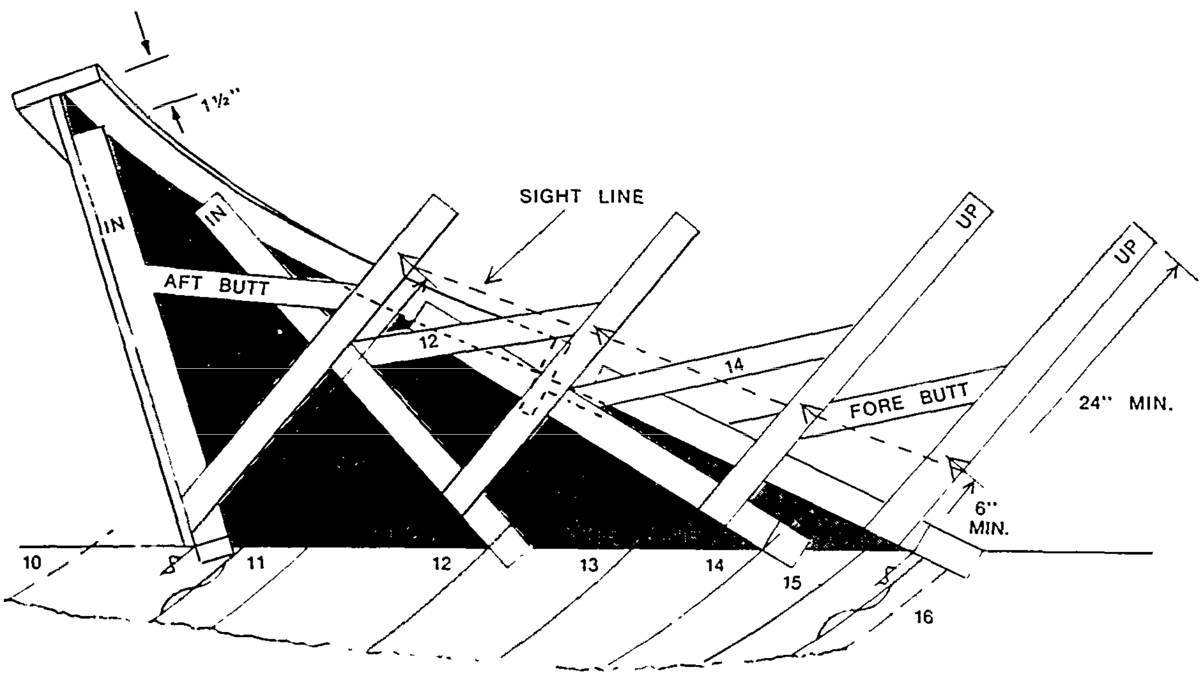


FIGURE 2-26: When longitudinals require twist, bending is performed first as described in *Figure 2-25*. Simple sight-line templates, shown above and in *Figure 2-3*, are employed to define an inverse curve in space. When a longitudinal is properly bent and twisted its spatial inverse curve becomes straight; it is the sight line. When a single longitudinal requires changing twist angles, in order to minimize production work, some designers limit twist, when possible, to just over a few frames rather than having it distributed over the entire length. Then, most of the longitudinal requires only single-axis bending.

3.0 SHAPING CURVED PARTS

3.1 Basic Methods

Where line heating is productively applied, there are two basic methods. One, featuring manual torch operation, is generally applied to plates requiring more than 50 millimeters in transverse curvature. These plates are usually first curved in a roller or press before being finished by line heating.

The second method employs a multi-torch line-heating machine as shown in *Figure 2.4.* This semi-automatic method is used for plates requiring up to 100 millimeters in transverse curvature over a span of about 2 meters and up to 600 millimeters in longitudinal curvature.

When line-heating workers become overloaded, more bending work is diverted to rollers or presses. For instance, plates requiring less transverse curvature, say 30 millimeters, would be first rolled or pressed. This diversion of work minimizes but does not eliminate line heating as the final process for achieving specified accuracy.

3.2 Accuracy

Just the introduction of line heating to accurately form curved parts will improve productivity. However, benefits will be significantly limited if line heating is applied in the absence of an effective program for statistical control of work processes. Such methods are routinely employed by the most productive shipbuilders.

The accuracy standards employed are not established by authority or general consent. They are the accuracies which are normally achieved expressed as *standard ranges* and *tolerance limils* for each process of construction. The statistically derived standard ranges, by definition, are the accuracies achieved by normally applied work for 95% $(\bar{x} \pm 2\sigma)$ of the items being worked. Each pair of tolerance limits (99.7% or $\bar{x} \pm 3\sigma$) includes allowances beyond its associated standard range for acceptable accuracy provided there is no upsetting of following work stages or specified end-product accuracy. Thus, tolerance limits are criteria for rework.

Pertinent standard ranges and tolerance limits derived from the world's most productive shipbuilding industry, are tabulated in *Figure 3-1.* They are based on what contributing shipyards have achieved with normally applied work. Thus, the so called standards are really descriptions of accuracies normally achieved which serve as baselines for comparing proposed improvements. In other words, they are means for managers to know where they are in line-heating technology matters.

In accordance with statistical-control theory as applied to manufacturing, the obligation to improve the system never ceases. Thus, the values for standard ranges and tolerance limits contained in *Figure 3-1 are* examined about every two years to insure that they continue to reflect normal performances. Changes since the values were first published in 1966, reflect improvements in accuracy due to the introductions of N/C lofting, marking and cutting and some automation of heating processes.

By close control of dimensional accuracy in the early stages of construction, the most productive shipbuilders have fewer problems later in the building process and so achieve a significant reduction in net man-hours needed. At the same time, they maintain structural strength acceptable to regulating societies and commercial value (quality and appearance) satisfactory to customers. Thus, the orders of accuracy they normally achieve as described in *Figure 3-1,* are prerequisite for competitive hull-construction.

Section	Sub-section	Item	Standard range	Tolerance limits	Remarks
Plates	Curved shell plate	In regard to the check line. for longitudinal	± 2.5	± 5.0	UNIT : mm
		〃 (for transverse	± 2.5	± 5.0	
		Gap between shell plate and section template.	± 2.5	± 5.0	

FIGURE 3-1 (a) Standard ranges and tolerance limits. Standard-range values indicate what contributing shipyards normally achieve for 95% of the items they monitor. Tolerance limits provide added allowances for the small number of items that exceed their standard ranges but which do not upset following work or specified end-product accuracy. The tables shown are fascimilies from "Japanese Shipbuilding Quality Standard (Hull Part) - 1979" published by the Research Committee on Steel Shipbuilding, The Society of Naval Architects of Japan. The publication serves to avoid disputes with customers and is generally accepted by classification societies. When a customer requires more severe accuracies, the document serves as a basis for negotiation.

UNIT : mm

Division		Deformation			
Section	Sub-section	Item	Standard Range	Tolerance limits	Remarks
Unfairness	Shell plate	Parallel part side	4	6	
		Parallel part bottom	4	6	
		Fore and aft part	5	7	
	Double bottom tank top plate		4	6	
	Bulkhead	Longl Bulk head Trans 〃 Swash Bulkhead	6	8	
	Strength deck	Parallel part (Between 0.6L※	4	6	
		Fore and aft part	6	9	
		Covered part	7	9	
	Second deck	Bare part	6	8	
		Covered part	7	9	
	Fore-castle deck Poop deck	Bare part	4	6	
		Covered part	7	9	
	Super Structure deck	Bare part	4	6	
		Covered part	7	9	
	Cross deck		5	7	
	House wall	Out side wall	4	6	
		Inside wall	4	6	
		Covered part	7	9	
	Interior member	Web of girder, trans	5	7	
	Floor and girder of double bottom		6	8	

FIGURE 3-1 (b): Standard ranges and tolerance limits for distortion removal. See Chapter 4.0.

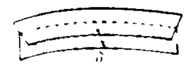
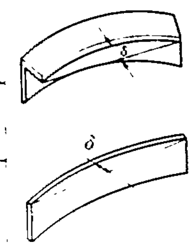
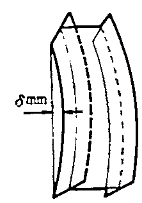
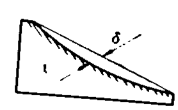
Division		Deformation			UNIT : mm
Section	Sub-section	Item	Standard Range	Tolerance limits	Remarks
Miscellaneous	Distorsion of girder and trans (at the part of upper edge and flange)	Length of span	5	8	
	Distorsion of longl. trans frame, beam and stiffner. (at the part of flange)	$\ell \leqq 1{,}000$	5	8	
		1, 000 ℓ · 3, 500	$3 + \frac{2\ell}{1000}$	$6 + \frac{2\ell}{1000}$	
		$\ell \geqq 3{,}500$	10	13	
	Distorsion of H pillar between decks.		4	6	
	Distorsion of cross tie.	Distorsion of fore and aft direction. δ cross tie only	6	10	
		Distorsion of fore and aft direction. δ cross tie · trans web	12	16	
	Distorsion of tripping bkt and Small stiffener with web plate.	Distorsion at the part of free edge.		t	
	Distorsion of face plate.		a $2 \cdot \frac{b}{100}$	$a = 5 \cdot \frac{b}{100}$	

FIGURE 3-1 (c): Standard ranges and tolerance limits for distortion removal. See Chapter 4.0.

3.3 Torch Operation

Where traditional heating methods are applied for fairing (removal of distortion), both divergent- and convergent-type torch tips are used. Line heating, as described in Part 1.2, applies heat along a relatively narrow region. Thus only convergent-type torch tips, such as for gas cutting, are used. Both types are illustrated in *Figure 3-2.*

As also described in Part 1.3, heating is carefully controlled because it is a main determinant for the degree of bending which occurs. Thus, only special heating torches or gas-cutting torches modified so that their oxygen jets are inoperable are used for line heating.

A standard flame as described in *Figure 3-3 is* optimum. During heating, the torch height is maintained so that the hottest part of the flame is in contact with the surface of the plate. During line heating of a specific plate, constant values for torch height and speed are maintained so that heat is uniformly applied.

The surface temperature is carefully controlled so *as* to preserve material quality. Temperature indicating crayons (such as Tempilsticks) are employed as necessary to maintain the surface temperature at 650°C (1 ,202°F) or less when cooling with water and 900°C (1,652°F) or less when air cooling.

Torch-travel speed varies primarily with plate thickness. Speed ranges employed by one shipbuilder for common steel when using oxyacetylene are:

Torch Speed (mm/min)	Steel Thickness (mm)
1,000	10 and thinner
600-700	13
550-600	16
450-500	20
300-450	20 and thicker

Figure 3-4, which reflects nearly the same data, is based on a summary of control experiments which were performed before 1960. The figure shows a practical safe range for application, when more care is needed (the most experienced workers) and a margin that should be maintained to avoid unacceptable material degradation.

When propane or ethylene is used, torch travel is a little slower. When natural gas (methane rich or equal) is used, travel is slower by 10 to 15%.

3.4 Roll Axis

Just as for a press or roller, a roll axis is needed for bending a plate by line heating. Heat lines are oriented parallel to a roll axis. Although computer-aided lofting is common, not all programs generate roll-axis marking instructions. In such cases, points which define a roll axis cart be located using sight-line templates as shown in *Figure 3-5* or by using sight-line data as in *Figure 3-6.* Regardless of the method used, the necessary points are marked on templates or patterns in the loft. Otherwise the work instructions are incomplete.

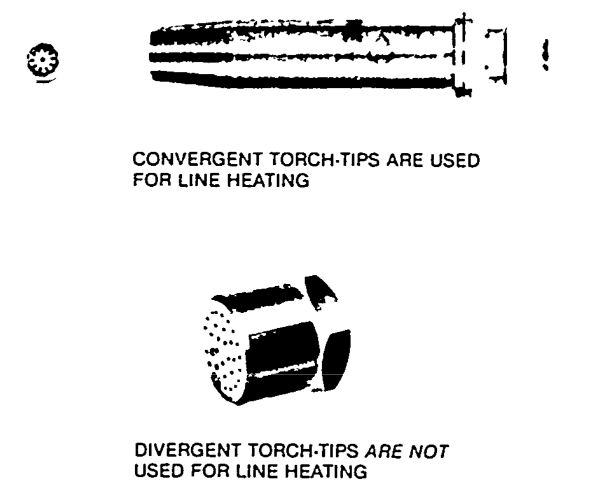


FIGURE 3-2: Torch tips. Specific torches and tips that are reported to be satisfactory for line heating are identified in Appendix C.

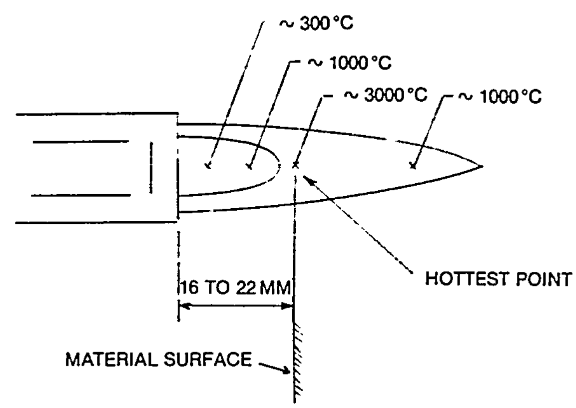


FIGURE 3-3: Maintaining a standard flame requires frequent inspections of the torch for leaks and frequent inspection of the torch tip. Damaged tips are discarded. Clogged tips are cleaned before use.

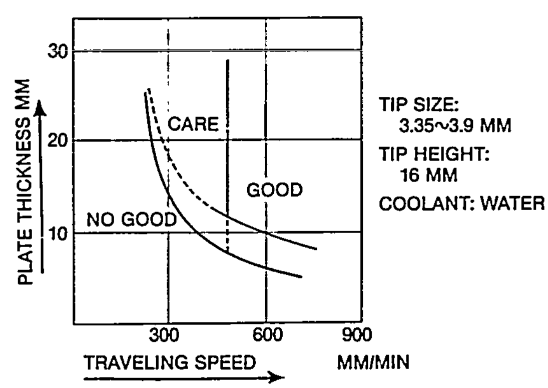


FIGURE 3-4: Practical speed ranges for line heating. From "Line Heating Method - A New Technique Taking the Place of Smith Work" as published in "Recent Developments in Shipbuilding Practice in Japan" by the Society of Naval Architects of Japan in 1961.

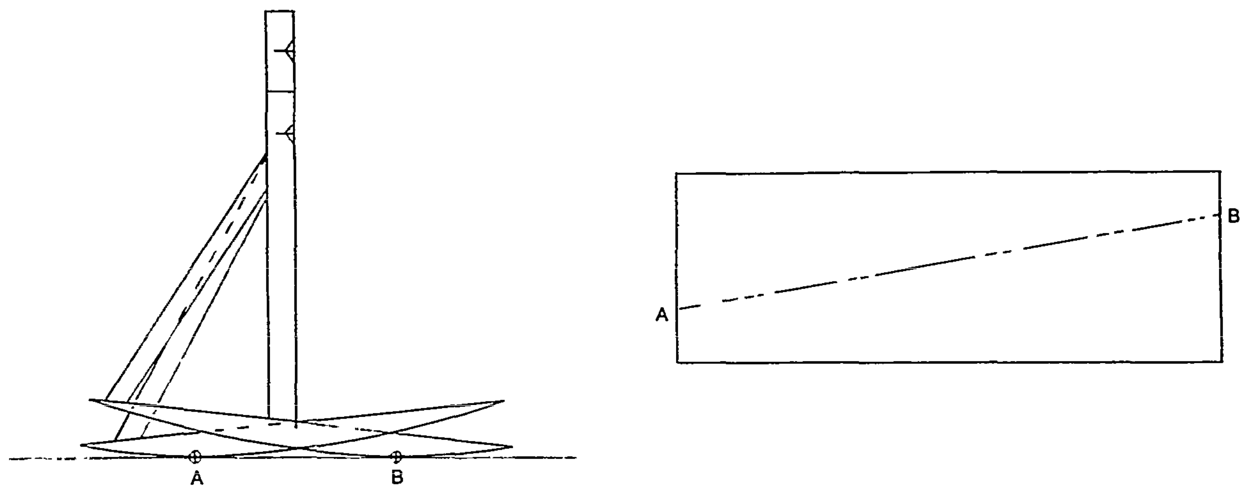


FIGURE 3-5: Marking a roll-axis. Both butt-templates are properly positioned relative to the flat plate and with their sight edges in the same plane. The points of tangency, A and B, are marked on the plate. The line AB is the roll axis. If the roll axis is not a straight line, the points of tangency for select frame templates are needed.

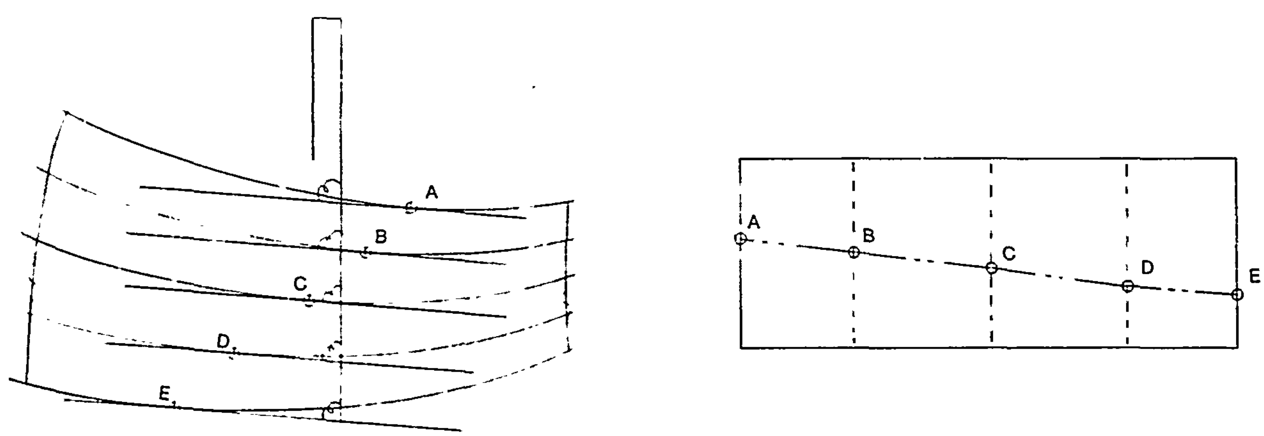


FIGURE 3-6: Determining a roll axis from patterns. Tangents are drawn to each frame line so that they are parallel to each other. The points of tangency define the roll axis.

3.5 Line Heating Work

When plates such as for certain side-shell regions, are to have less than 50 millimeters in transverse curvature and little or no twist, they are productively formed by line heating. Processing by roller or press is not needed. There are five basic steps:

- marking (includes defining a roll axis and establishing heat lines parallel to it),
- stressing (not always required, creates a mechanical stress with wedges, dogs, etc., upon which thermal stress is superimposed),
- initial heating (when properly applied, accomplishes nearly all bending required without over bending),
- checking (setting templates and determining finish bending required), and
- finish heating (accomplishes just that amount of bending required for prescribed curvature).

Although *checking is* identified as a distinct step, a certain amount of checking is performed during other steps. A more detailed description of the five basic steps is provided in *Figure 3-7.*

3.6 Line Heating After Mechanical Bending

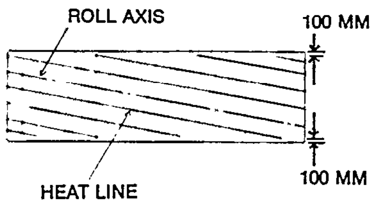
Plates having more than 50 millimeters in transverse curvature are first formed by a roller or press and then are finished by line heating. Except for mechanical bending, work proceeds almost as described for side-shell curvature in *Figure 3-7. Figures 3-8* through 3-12 show typical line-heating work in conjunction with mechanical bending. Scheduling contingencies sometimes require shifting work such as from a line-heating slab to a bending machine. Regardless of where the work takes place, finishing by line heating is usually required in order to achieve accuracies that are within tolerance limits.

3.7 LongitudinaIs

A number of methods are used to mechanically bend structural sections such as angles and built-up tees. Finishing by line heating is often necessary for accuracy purposes. Also, frame-bending machines are unable to bend the ends of longitudinals unless extra material or margins are provided for grasping purposes. Some shipbuilders who have perfected A/C as a means to improve productivity, cut longitudinals to their design lengths. The straight ends which remain after mechanical bending are then bent by triangle heating; see *Figure 3-13.*

As frame-bending machines are not usually designed to bend in the plane of a beam flange, triangle heating as shown in *Figure 3-14 is* used. A technique for heating a triangle is described in Appendix D. Also, line heating applied as in *Figure 3-15* is an effective method employed to twist longitudinrds.

1ST STEP: MARKING

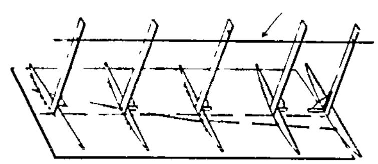


SET TEMPLATES FOR EACH BUTT AND A NUMBER OF FRAMES SUFFICIENT TO ASSESS THE RATE OF REQUIRED BEND AND TWIST.

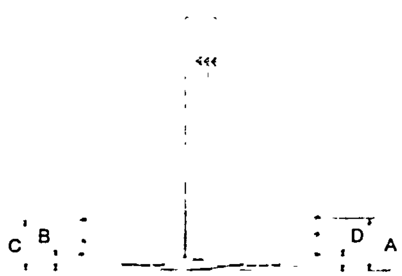
MARK A ROLL AXIS: SEE PART 3.4

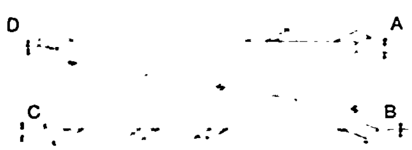
MARK HEAT LINES AT 200 MILLIMETERS APART AND PARALLEL TO THE ROLL AXIS BUT AVOID MARKING ANY HEAT LINE WITHIN 100 MILLIMETERS OF A SEAM.

2ND STEP: STRESSING



RESET THE TEMPLATES AND MEASURE THE HEIGHTS A, B, C AND D WHICH RELATE TO PLATE CORNERS.





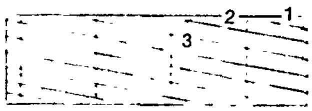
PLACE WOOD BLOCKS OR WEDGES SO THAT EACH PLATE CORNER IS SUPPORTED AT ITS RESPECTIVE MEASURED HEIGHT.

IF DUE TO JUST GRAVITY THE PLATE CURVATURE CONFORMS WITH THE TEMPLATES WHILE THEIR SIGHT EDGES AND SIGHT POINTS ARE IN ALIGNMENT WITH EACH OTHER, LINE HEATING IS NOT REQUIRED. HOWEVER, WITH EXPERIENCE A FORMAL SUCH CHECK IS NOT GENERALLY REQUIRED.

IF DUE TO JUST GRAVITY THE PLATE CURVATURE DOES NOT CONFORM WITH THE TEMPLATES, LINE HEATING IS REQUIRED AND THE LOWEST CORNERS SHOULD BE FORCED DOWN AS SHOWN.

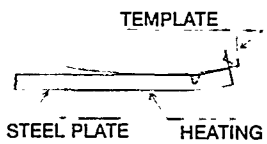
FIGURE 3-7 (a) Line heating - typical side-shell.

3RD STEP: INITIAL HEATING

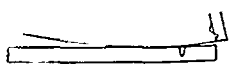


SET TORCH FOR A STANDARD FLAME (PART 3.3) AND HEAT IN THE ORDER AND DIRECTIONS SHOWN, I.E., 1, 2, 3, ETC., AT A PRESCRIBED TORCH SPEED.

AFTER THE FIRST HEAT PASS USE A SIGHT-LINE TEMPLATE TO DETERMINE IF THE TORCH SPEED SHOULD BE ADJUSTED.

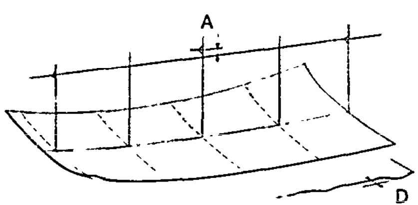


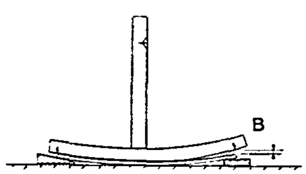
IF OVERBENT, INCREASE TORCH SPEED.



IF UNDERBENT, DECREASE TORCH SPEED.

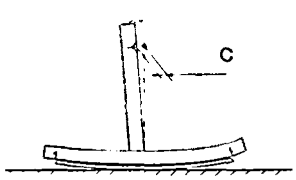
4TH STEP: CHECKING





REMOVE DOGS AND SET SIGHT-LINE TEMPLATES.

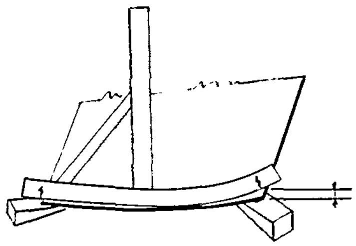
MEASURE VARIATION OF:
A. LONGITUDINAL CURVATURE
B. TRANSVERSE CURVATURE
C. TWIST
D. SEAM SMOOTHNESS.



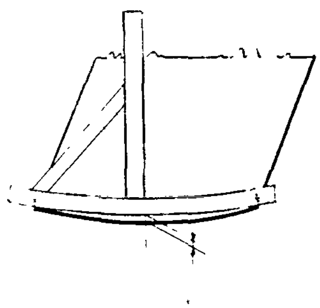
IF THE VARIATIONS ARE WITHIN TOLERANCE LIMITS (PART 3.2) NO FURTHER BENDING WORK IS REQUIRED. IF NOT, FINISH HEATING IS REQUIRED.

FIGURE 3-7 (b): Line heating - typical side-shell.

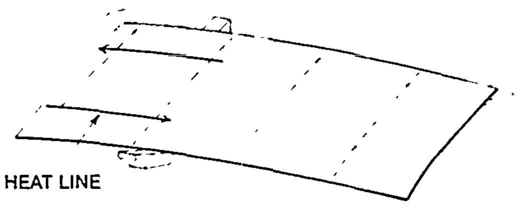
5TH STEP: FINISH-HEATING - THERE ARE FINISH-HEATING ALTERNATIVES DEPENDENT UPON THE NATURE AND EXTENT OF VARIATION DISCLOSED IN CHECKING. THOSE SHOWN ARE TYPICAL. THROUGH EXPERIENCE, OTHER SUCH METHODS ARE DEVELOPED.

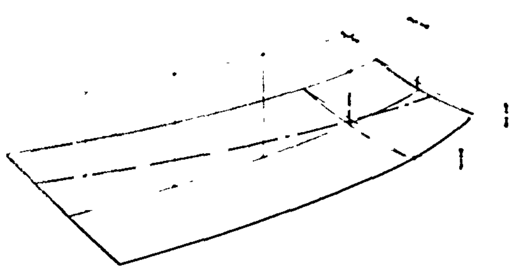


WHEN THERE IS INSUFFICIENT TRANSVERSE CURVATURE BY A RELATIVELY LARGE AMOUNT, WEDGES ARE PLACED AS SHOWN AND HEAT IS APPLIED IN THE REGION OUT OF TOLERANCE ALONG LINES THAT ARE PARALLEL TO AND IN BETWEEN PREVIOUS HEAT LINES. IF THE CURVATURE IS INSUFFICIENT BY A SMALL AMOUNT, WEDGES TO SUPPORT CORNERS ARE NOT REQUIRED.



WHEN THERE IS OVER CURVATURE WHICH EXCEEDS THE TOLERANCE LIMIT, THE PLATE IS TURNED OVER, SUPPORTED BY WEDGES, AND HEATED ALONG LINES AS SHOWN.





WHEN THERE IS INSUFFICIENT TRANSVERSE CURVATURE AND TOO MUCH TWIST, THE WEDGES AND DOGS ARE RESET AS FOR THE 2ND STEP (STRESSING) AND LINE HEATING IS APPLIED ACROSS THE ROLL AXIS AS SHOWN.

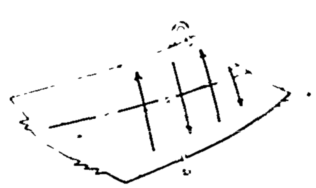
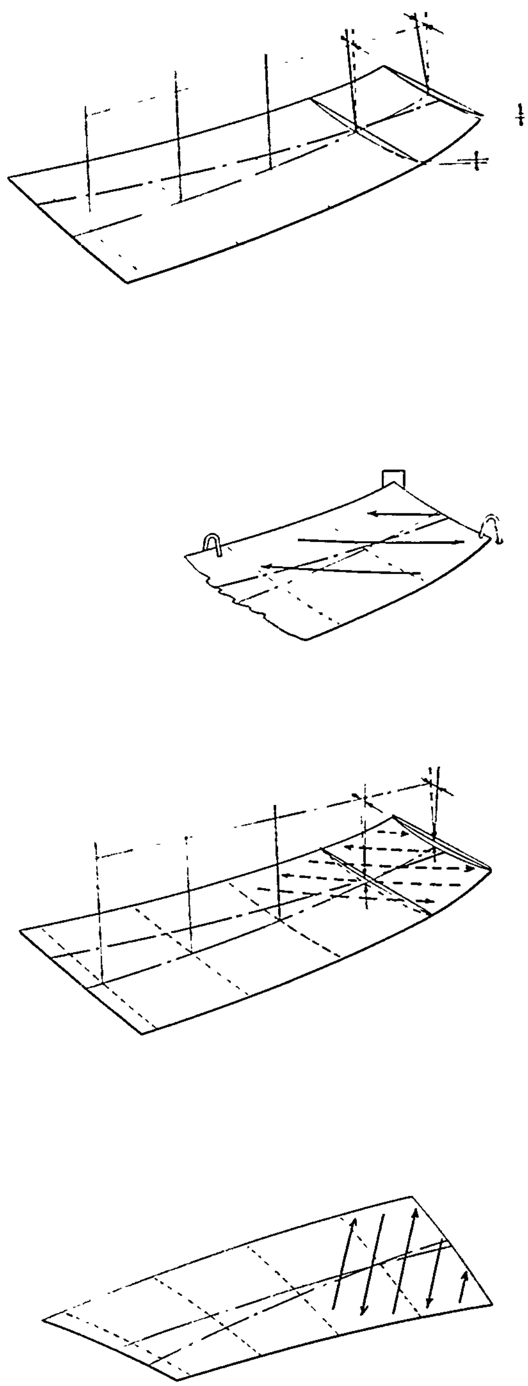


FIGURE 3-7 (c): Line heating - typical side-shell.

5TH STEP: FINISH HEATING (CONTINUED)

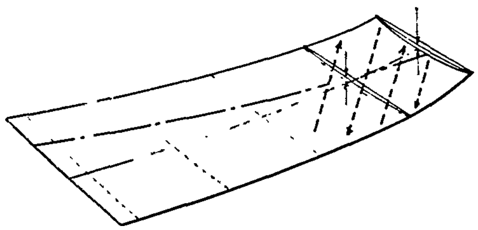


WHEN THERE IS INSUFFICIENT TRANSVERSE CURVATURE AND NOT ENOUGH TWIST, THE PLATE IS WEDGED AND DOGGED AS SHOWN HEAT IS APPLIED ALONG LINES AT ACUTE ANGLES TO THE ROLL AXIS AS SHOWN.

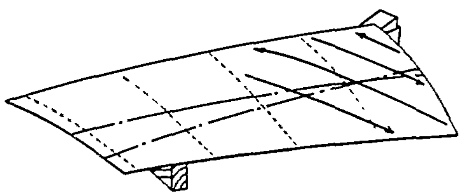
WHEN THERE IS EXCESS TRANSVERSE CURVATURE AND TOO MUCH TWIST THE PLATE IS TURNED OVER AND HEAT IS APPLIED ALONG LINES AT ACUTE ANGLES TO THE ROLL AXIS AS SHOWN.

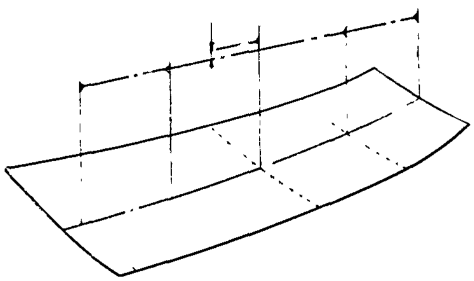
FIGURE 3-7 (d): Line heating - typical side-shell.

5TH STEP: FINISH HEATING (CONTINUED)



WHEN THERE IS TOO MUCH TRANSVERSE CURVATURE AND NOT ENOUGH TWIST THE PLATE IS TURNED OVER AND HEATED ALONG LINES RELATIVE TO THE ROLL AXIS AS SHOWN.





WHEN JUST LONGITUDINAL CURVATURE IS INSUFFICIENT, HEAT IS APPLIED TO PAIRS OF OPPOSITE TRIANGLES AS SHOWN. THE FIRST PAIR IS LOCATED WHERE THE MOST VARIATION FROM PRESCRIBED LONGITUDINAL CURVATURE EXISTS. IF PRESCRIBED CURVATURE IS STILL NOT WITHIN TOLERANCE LIMITS, A SECOND PAIR IS HEATED WHEREVER NEEDED MOST AND SO ON. GENERALLY, HEATING A PAIR OF TRIANGLES WILL BRING THE SIGHT POINT AT MID FRAME ABOUT 10 MILLIMETERS CLOSER TO THE SIGHT LINE. WITHIN EACH TRIANGLE HEAT IS APPLIED WITH A WEAVING MOTION STARTING AT THE APEX.

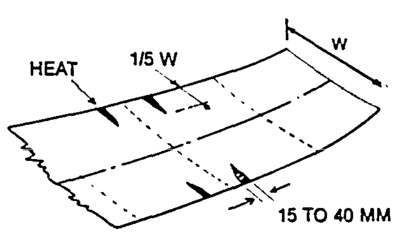
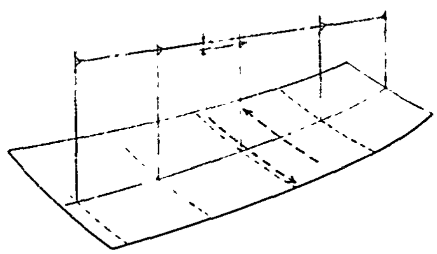
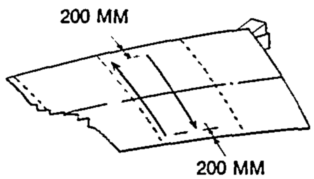


FIGURE 3-7 (e): Line heating - typical side-shell.

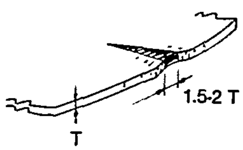
5TH STEP: FINISH HEATING (CONTINUED)



WHEN JUST LONGITUDINAL CURVATURE IS EXCESSIVE, THE PLATE IS TURNED OVER, SUPPORTED WITH WEDGES AS NECES. SARY TO MAINTAIN TWIST, AND HEATED ALONG LINES LOCATED AT MID LENGTH OF THE PLATE AND PARALLEL *TO* FRAME LINES. CARE IS TAKEN TO INSURE THAT HEAT IS NOT APPLIED WITHIN 200 MILLIMETERS OF SEAMS.



WHEN A SEAM IS NOT FAIR BY HAVING A RISE, HEAT IS APPLIED BY WEAVING MOTION TO A TRIANGLE AS SHOWN.



WHEN A SEAM IS NOT FAIR BY HAVING A DEPRESSION, HEAT IS APPLIED BY WEAVING MOTION TO A NARROW RECTANGLE ORIENTED AS SHOWN. CARE IS TAKEN TO INSURE THAT HEAT IS NOT APPLIED WITHIN 100 MILLIMETERS OF THE SEAM.

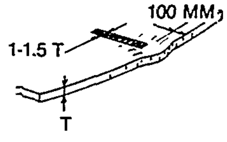


FIGURE 3-7 (f): Line heating - typical side-shell.

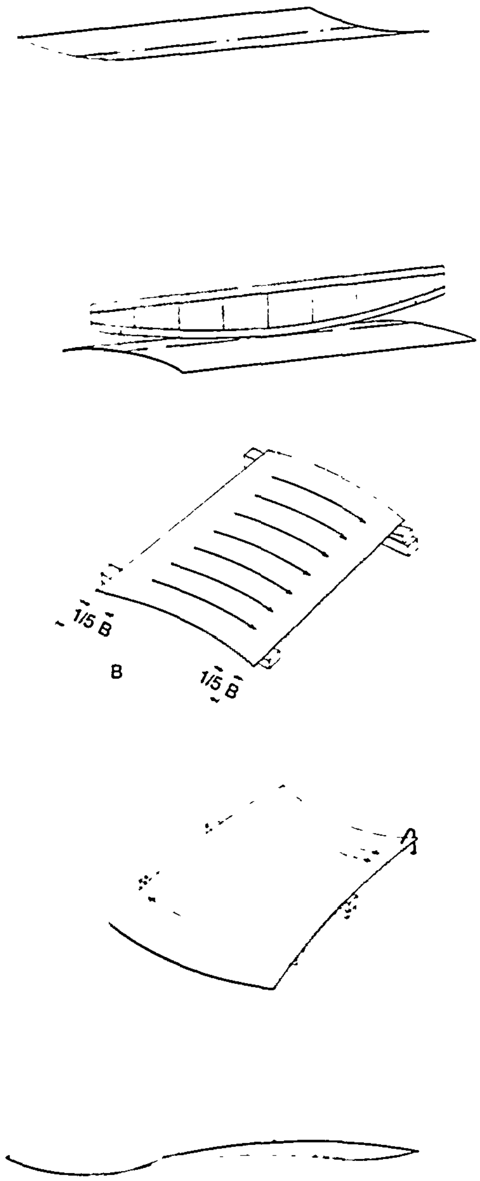
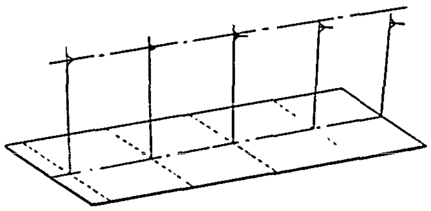
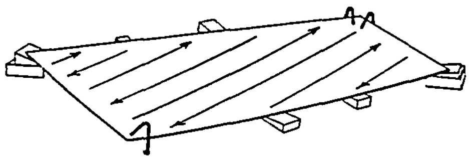


FIGURE 3.8. Line hearing - saddle plate.

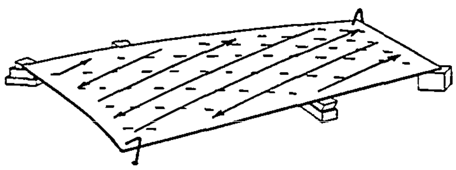


USING SIGHT-LINE TEMPLATES THE DEGREE OF TWIST IS ASSESSED. BEND AND HEAT LINES ARE MARKED.

MECHANICAL BENDING IS PERFORMED.

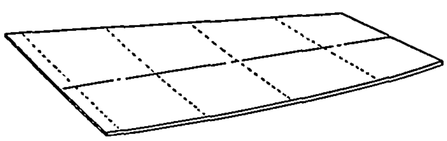


WEDGES AND DOGS ARE POSITIONED, AND HEATING IS PERFORMED TAKING CARE NOT TO HEAT WITHIN 100 MILLIMETERS OF SEAMS.



THE PLATE IS TURNED OVER, HEAT LINES ARE MARKED, WEDGES AND DOGS ARE POSITIONED, AND HEATING IS PERFORMED IN ACCORDANCE WITH A SCHEME, AS SHOWN, WHICH IS OPPOSITE THAT PREVIOUSLY USED.

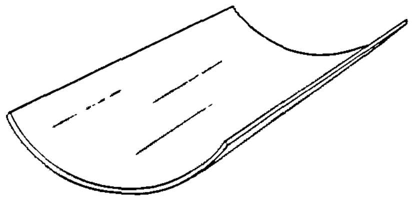
THE PLATE IS TURNED OVER, CHECKED WITH THE SIGHT-LINE TEMPLATES AND FINISHED HEATED AS NECESSARY.



FINISHED PLATE.

FIGURE 3-9: Line heating - twisted plate.

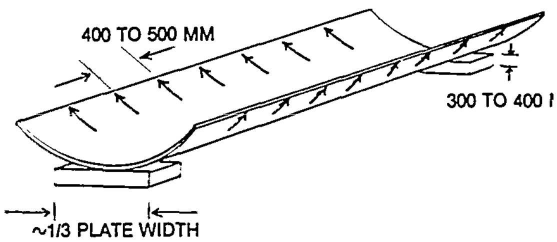
USING SIGHT-LINE TEMPLATES THE ROLL AXIS IS DETERMINED AND THE DEGREE OF REQUIRED CURVATURE IS ASSESSED.



HEAT LINES ARE MARKED STRAIGHT IN CHALK OR STONE PENCIL AS NEEDED TO ANTICIPATE THE CHANGING RADII.

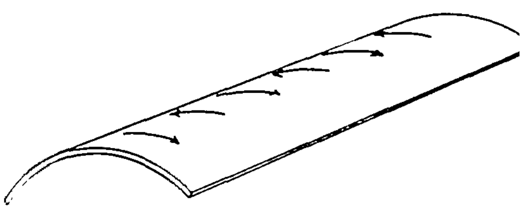
MECHANICAL BENDING IS PERFORMED.

HEATING IS PERFORMED TO ACHIEVE SLIGHTLY LARGER RADII THAN INDICATED BY THE TEMPLATES FOR TRANSVERSE CURVATURE.



THE PLATE IS SUPPORTED BY BLOCKS, MARKED AND HEATED, AS SHOWN, TO INTRODUCE LONGITUDINAL CURVATURE.

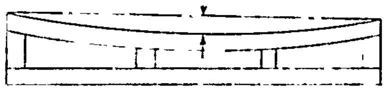
THE SIGHT-LINE TEMPLATES ARE USED FOR CHECKING. FINISH HEATING IS PERFORMED AS REQUIRED.



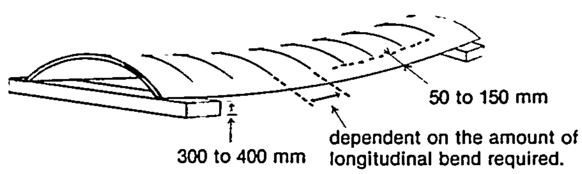
IF CHECKING DISCLOSES EXCESSIVE LONGITUDINAL BENDING, THE PLATE IS TURNED OVER AND HEATEO, AS SHOWN, ON LINES WHICH ARE 2/3 THE WIDTH OF THE PLATE.

FIGURE 3-10: Line heating - bilge strake.

THE TRANSVERSE RADIUS ACHIEVED BY PRESS BENDING IS LESS THAN WHAT THE DESIGN REQUIRES BY 5 TO 10% DEPENDING ON THE LONGITUDINAL BENDING REQUIRED. WHEN LINE HEATING TO INTRODUCE LONGITUDINAL CURVATURE, THE TRANSVERSE RADIUS INCREASES



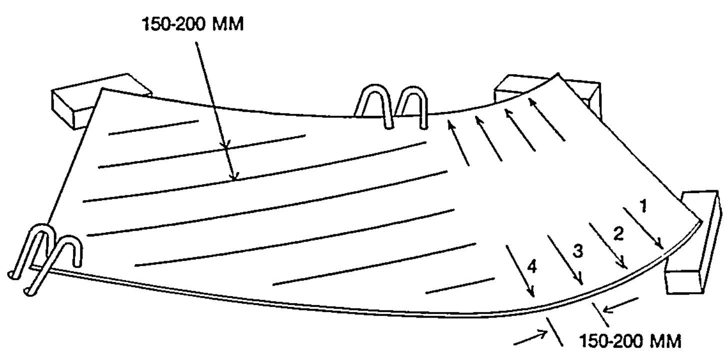
A PROFILE TEMPLATE IS USED TO ASSESS THE LONGITUDINAL CURVATURE REQUIRED.



HEAT IS APPLIED OVER THE WIDTH OF THE PLATE ALONG LINES AS SHOWN LINES ARE SPACED APART DEPENDENT ON THE PLATE WIDTH AND THICKNESS, ON THE TRANSVERSE CURVATURE ACHIEVED BY PRESSING AND ON THE LONGITUDINAL CURVATURE REQUIRED. INEXPERIENCED WORKERS START WITH LINES ABOUT 100 MILLIMETERS APART AND THEN AFTER CHECKING WITH TEMPLATES THEY HEAT ALONG INTERVENING LINES AS NECESSARY

FIGURE 3-11: Line heating - stem plate.

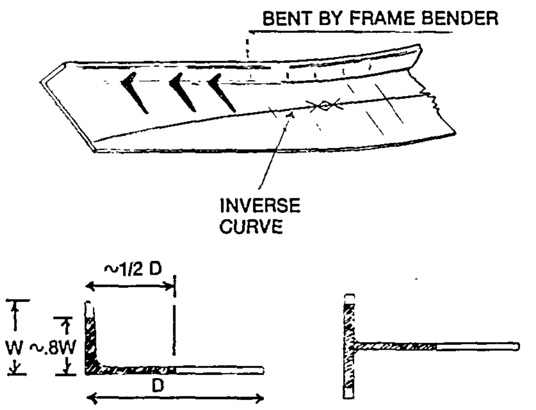
SIGHT-LINE TEMPLATES ARE SET IN ORDER TO MARK ROLL AXES AND HEAT LINES AS SHOWN. THE HEAT LINES ON THE LEFT TERMINATE 200 MILLIMETERS FROM SEAMS. THE HEAT LINES ON THE RIGHT DO NOT EXTEND INTO THE MID ONE-THIRD OF THE PLATE WIDTH.



DOGS AND BLOCKS INTRODUCE STRESS.

HEATING IS PERFORMED FIRST ON THE RIGHT IN THE SEQUENCE NOTED.

FIGURE 3-12: Line heating - cant plate.



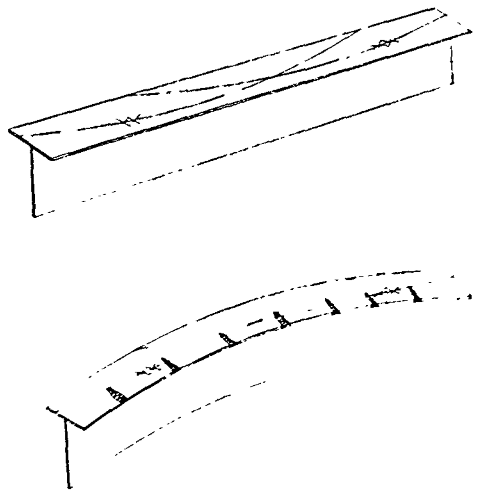
USE THE INVERSE CURVE TO ASSESS CURVATURE REQUIRED.

MARK TRIANGLES.

APPLY HEAT.

CHECK AND REAPPLY HEAT AS NECESSARY UNTIL THE INVERSE CURVE BECOMES A STRAIGHT LINE.

FIGURE 3-13: Bending ends of longitudinals by triangle heating.



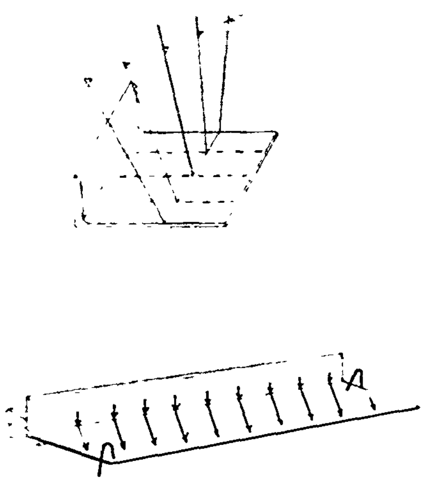
USE THE INVERSE CURVES TO ASSESS CURVATURE REQUIRED.

MARK TRIANGLES.

APPLY HEAT.

CHECK AND REAPPLY HEAT AS NECESSARY UNTIL INVERSE CURVES BECOME STRAIGHT LINES.

FIGURE 3-14: Bending a longitudinal in the plane of its flange.



USE SIGHT-LINE TEMPLATES TO ASSESS THE AMOUNT OF TWIST REQUIRED.

MARK HEAT LINES.

POSITION WEDGES AND DOGS.

APPLY HEAT

CHECK WITH SIGHT-LINE TEMPLATES.

FIGURE 3-15: Twisting longitudinals.

4.0 DISTORTION REMOVAL

Feedback from statistical analyses disclosed that even where the best known techniques are employed to avoid distortion caused by heat processes, enough distortion remains to detract from the efficiency of following assembly work. Thus for productivity reasons, line heating is routinely applied for fairing after gas-cutting parts, sub-block-assembly, and block assembly. In each such manufacturing level, line heating for removing distortion is a regular work process equivalent to marking, cutting, fitting or welding. Line heating is also applied for fairing after erection, but is required in significantly lessor amounts than when not applied throughout the manufacturing levels. Removing distortion before it can affect a succeeding work stage is a proven technique for improving productivity for an entire hull-construction process.

As compared to conventional methods for fairing, properly applied line heating produces more accurate finishes and has less impact on the strength characteristics of materials. However, some shrinkage is inherent and line heating cannot be applied to all fairing problems. In Japan where such techniques are most advanced, about 10% of required fairing work is performed by other methods, e.g., spot heating, triangle heating, red-hot heating and mechanical bending. Basic classifications of the various fairing methods are shown in *Figure 4-1.*

Surrounding members often impact on the effectiveness of fairing methods for a particular distorted region. Pre-stressing with jigs, jacks, gravity, etc., followed by line, triangle or spot heating is often effective. Extreme indentations or creases usually require red-hot heating and pressing or hammering (blacksmithing).

As for forming curved plates, water cooling is effective for most fairing work but is not permitted for high-tensile steels. Air cooling is effective for the latter and, regardless of materials, also for fairing the surfaces of subassemblies including blinks. Applications of some fairing techniques are illustrated in *Figures 4-2* through 4-14.

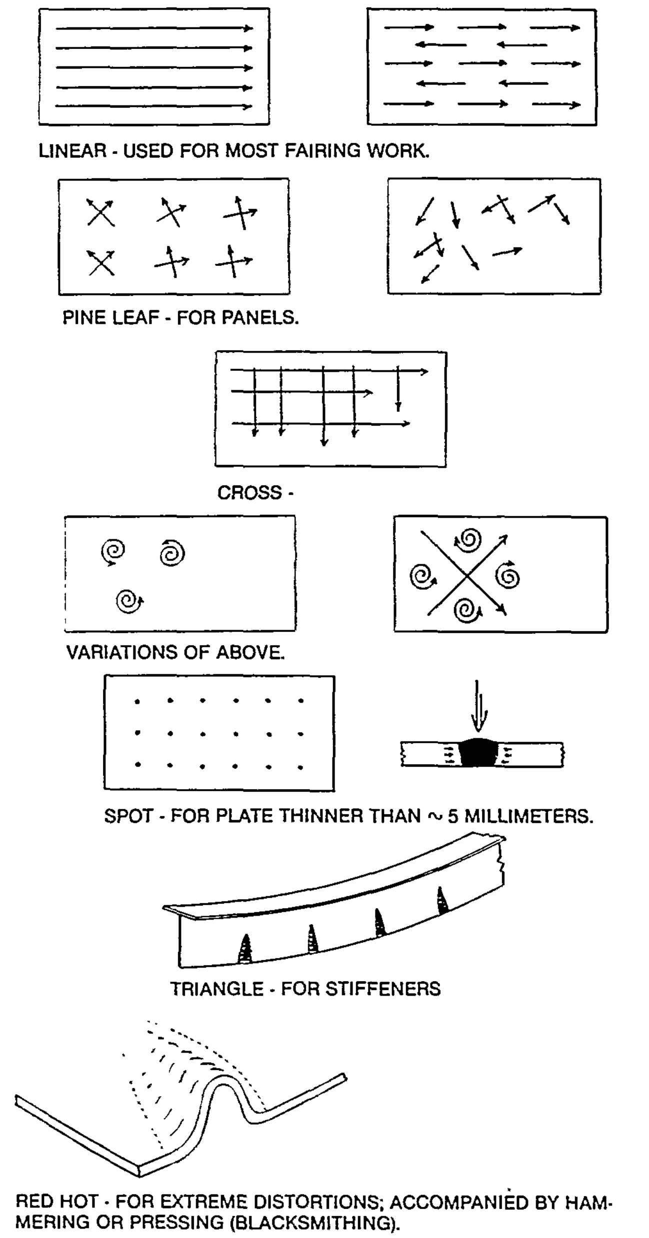
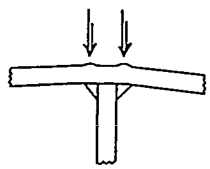
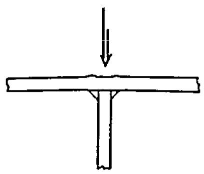


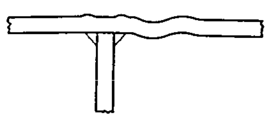
FIGURE 4-1: Classification of heating methods for fairing work.



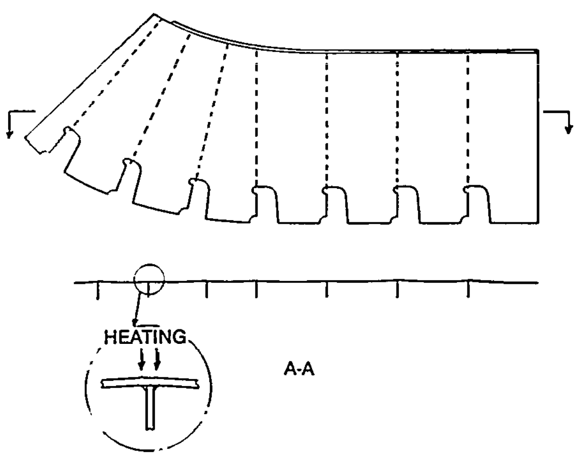
LINEAR HEATING IS APPLIED ON THE BACK SIDE FROM FILLET WELDS. TORCH TRAVEL IS UNIFORM AND HEAT IS APPLIED FROM PLATE EDGE TO PLATE EDGE.



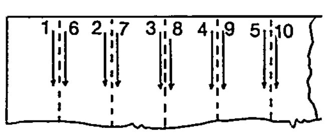
WHEN DISTORTION IS SMALL OR PLATE IS THIN, ONLY ONE HEAT LINE IS NECESSARY.



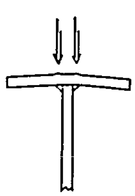
TOO MUCH HEATING BECAUSE OF SLOW TORCH TRAVEL CAN CAUSE SECONDARY DISTORTION. IT IS PREFERABLE TO APPLY HEAT QUICKLY AND REHEAT AS NECESSARY.



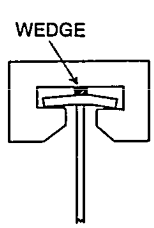
LINEAR HEATING IS APPLIED TO THE BACK SIDE FROM ALL STIFFENER WELDING.



ALTHOUGH THE HEATING SEQUENCE IS NOT VITAL, IF A DOUBLE-TIPPED TORCH IS NOT USED THE SEQUENCE SHOWN IS SUGGESTED.

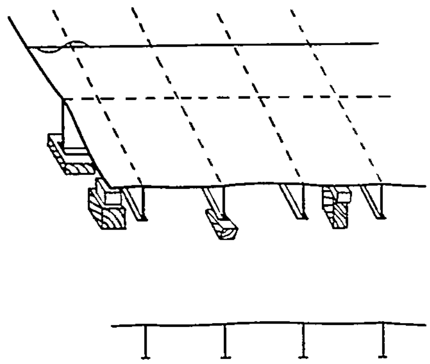


LINEAR HEATING IS ALSO APPLIED TO FACE PLATES OF GIRDERS AND WEB FRAMES AND TO FLANGES OF BUILT-UP TEES.

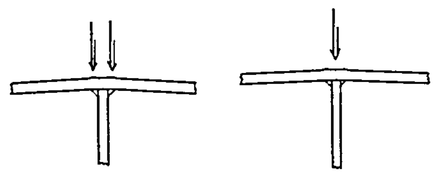


WHEN THE DISTORTION IS RELATIVELY LARGE A MECHANICAL STRESS IS APPLIED BEFORE HEATING.

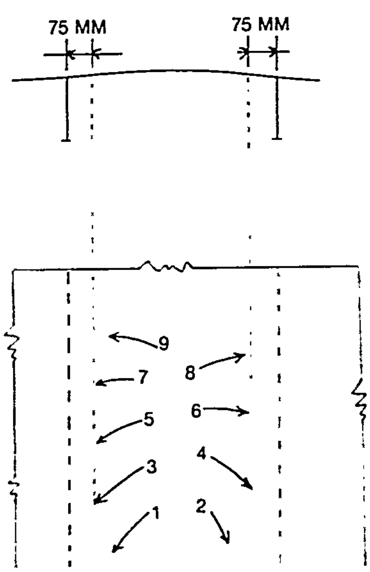
FIGURE 4-2: Fairing sub-assembled floors, girders, transverses, etc. When distortion is small, water cooling is not necessary.



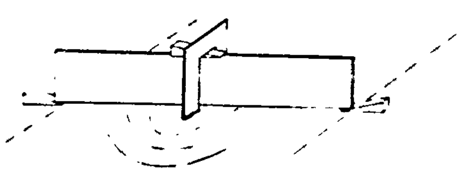
USE WOOD BLOCKS AND WEDGES TO MAINTAIN THE PANEL LEVEL ALTHOUGH THE SEQUENCE IS NOT VITAL HEATING IS APPLIED FIRST IN THE CENTER AND THEN OUTWARDS TO THE EDGES.



LINEAR HEATING IS APPLIED TO THE BACK SIDE OF ALL STIFFENER WELDING. IF DISTORTION IS SMALL OR THE PLATE IS THIN ONLY ONE FLAME IS REQUIRED. WATER COOLING CLOSE TO THE FLAME PREVENTS EXPANSION.

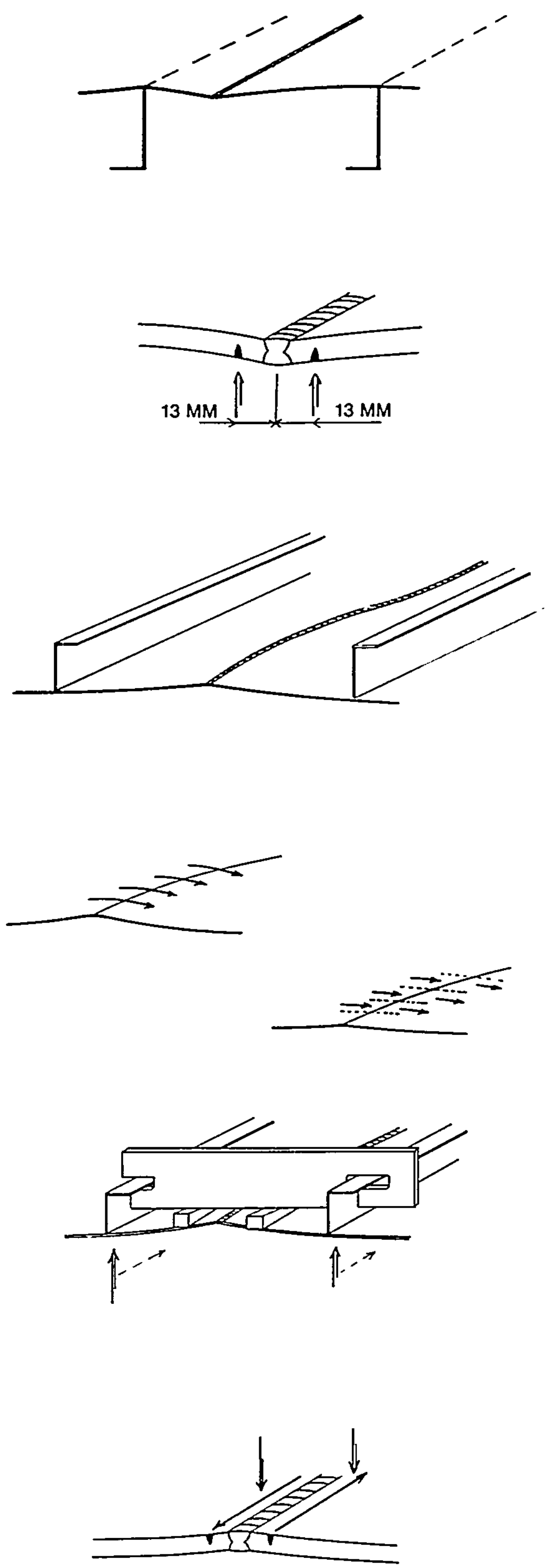


IF THE PANEL REMAINS DISTORTED BETWEEN STIFFENERS, LINEAR HEAT THE CONVEX SIDE AS SHOWN. SOMETIMES WHEN DISTORTION IS REMOVED FROM BETWEEN A PAIR OF STIFFENERS, NEIGHBORING PANEL SURFACES BECOME FAIR. IF THE DISTORTION PERSISTS, AGAIN LINEAR HEAT THE BACK SIDE OF STIFFENER WELDS AND IF NECESSARY AGAIN LINEAR HEAT THE CONVEX SIDE AS SHOWN.



WHEN THE DISTORTION BETWEEN STIFFENERS IS CONCAVE A STRONG-BACK JIG IS USED TO PULL THE PANEL UP BEFORE HEATING

FIGURE 4-3: Fairing assembled flat-panels. e.g., decks and bulkheads. Flat panels that have only small amounts of distortion are sometimes faired after hull erection if they are then readily accessible.



WHEN THE SEAM IS STRAIGHT, FIRST LINEAR HEAT ON THE BACK SIDE FROM FILLET WELDS.

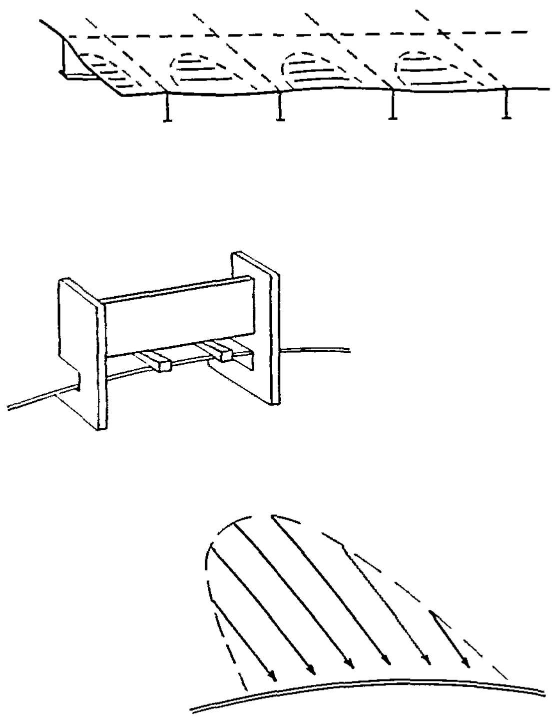
THEN LINEAR HEAT AS SHOWN ON BOTH SIDES OF THE WELD.

WHEN THE SEAM HAS CURVATURE LINEAR HEAT ACROSS THE SEAM AS SHOWN. OTHER HEATING PATTERNS ARE USED SUCH AS STARTING AT THE SEAM AND STRAIGHT OR AS A CHEVRON; THEIR EFFECTS DIFFER BY LITTLE.

AFTER COOLING, WHERE DEFORMATION REMAINS, LINEAR HEAT AGAIN AS SHOWN AND IF NECESSARY, AGAIN HEAT ALONG STIFFENER WELDS FROM THE BACK SIDE.

PERSISTENT DISTORTION REQUIRES MECHANICAL STRESSING AS SHOWN AND LINEAR HEATING APPLIED AT 13 MILLIMETERS FROM BOTH SIDES OF THE SEAM.

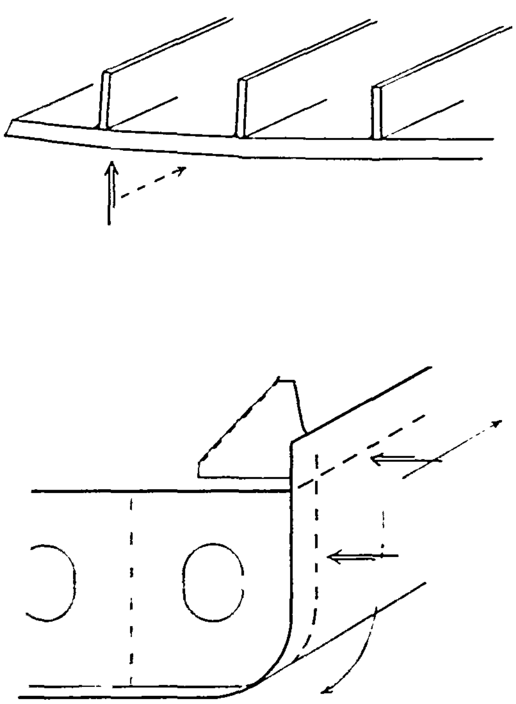
FIGURE 4-4: Fairing in way of a seam.



A JIG IS EMPLOYED TO CREATE MECHANICAL STRESS.

LINEAR HEATING IS APPLIED AS SHOWN.

FIGURE 4-5: Fairing panel edges.



LINEAR HEATING IS APPLIED ON THE BACK SIDE FROM FILLET WELDS FROM THE BUTT TO SOME DISTANCE BACK FROM THE BUTT AS REQUIRED. WATER COOLING IS USUALLY NOT NEEDED.

LINEAR HEATING IS APPLIED ON THE BACK SIDE OF FILLET WELDS AS SHOWN WHEREVER DISTORTION DETRACTS FROM THE NEEDED ACCURACY OF ERECTION BUTTS AND SEAMS.

FIGURE 4-6: Fairing erection joints. This work is very important because it impacts significantly on productivity during hull erection. Traditional shipbuilders leave these welds free until after erection. Welding them in a building dock costs at least three times more than costs for welding during block assembly where A/C is practiced.

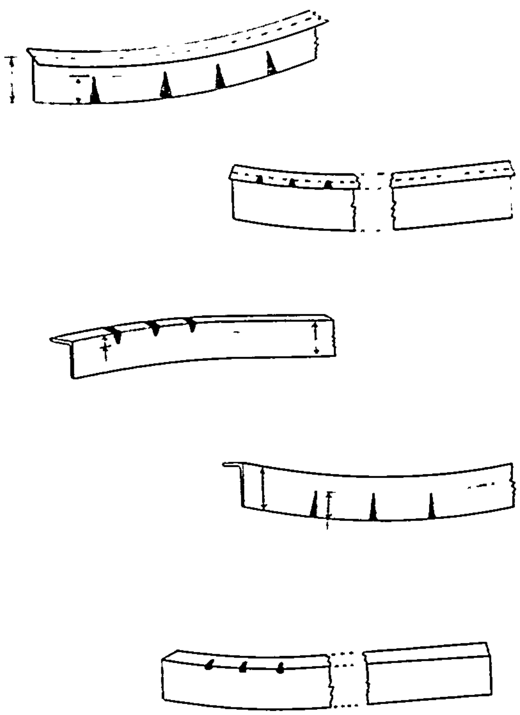


FIGURE 4-7: Straightening stiffeners. Triangle heating is applied in locations shown.

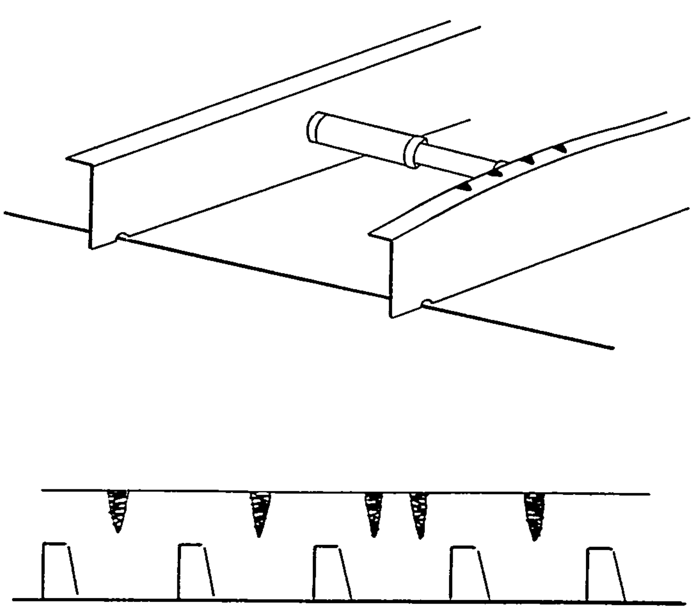
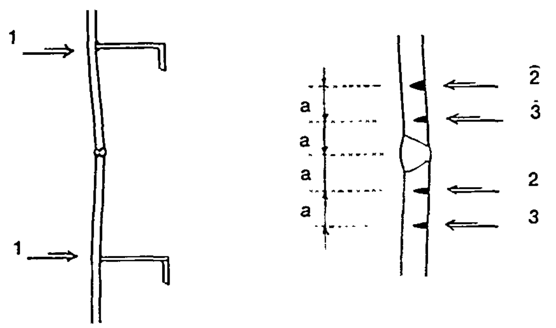
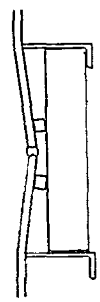


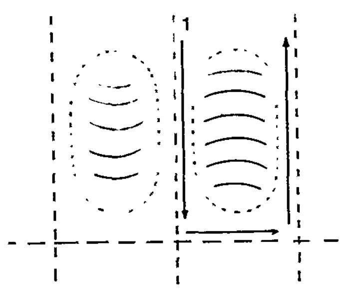
FIGURE 4-8: Fairing stiffeners, curtain plates, etc.



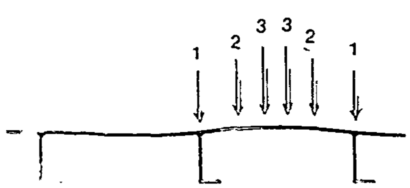
WHEN DISTORTION IS SMALL AND ENCOMPASSES A WELD HEAT IS APPLIED RAPIDLY AT ABOUT 90 CENTIMETERS/MINUTE ON THE BACK SIDE OF THE FILLET WELDS AS SHOWN, 1. THEN HEAT IS APPLIED FROM THE INSIDE ALONG LINES SPACED FROM THE WELD AS SHOWN, 2. IF DISTORTION REMAINS HEAT IS APPLIED ALONG ADDITIONAL LINES, 3.



WHEN DISTORTION IS LARGE, MECHANICAL STRESS IS FIRST APPLIED (HYDRAULIC JACK, ETC.) BEFORE HEATING AS DESCRIBED ABOVE. CARE IS TAKEN NOT TO PRESS THE PLATE OUT MORE THAN ABOUT 3 MILLIMETERS DURING ONE CYCLE. PRESSING AND HEATING CONTINUE FOR AS MANY CYCLES AS NEEDED.



WHEN DISTORTION DOES NOT ENCOMPASS A WELD, HEAT IS APPLIED ALONG PATH 1 FROM THE OUTSIDE CLOSE TO THE BACKSIDE OF FILLET WELDS FOR FRAMES AND GIRDERS.



HEAT IS APPLIED ALONG PATHS 2 AND 3 IF NECESSARY. SOMETIMES THE STRAIGHTENING WORK APPLIED AS DESCRIBED WILL ALSO STRAIGHTEN THE ADJACENT PANEL SHOWN. IF NOT, LINEAR HEAT IS APPLIED ALONG PATHS 2 AND 3 FROM THE INSIDE. WATER COOLING IS FROM THE OUTSIDE TO PREVENT ACCUMULATIONS INSIDE.

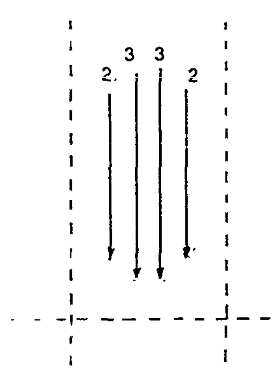
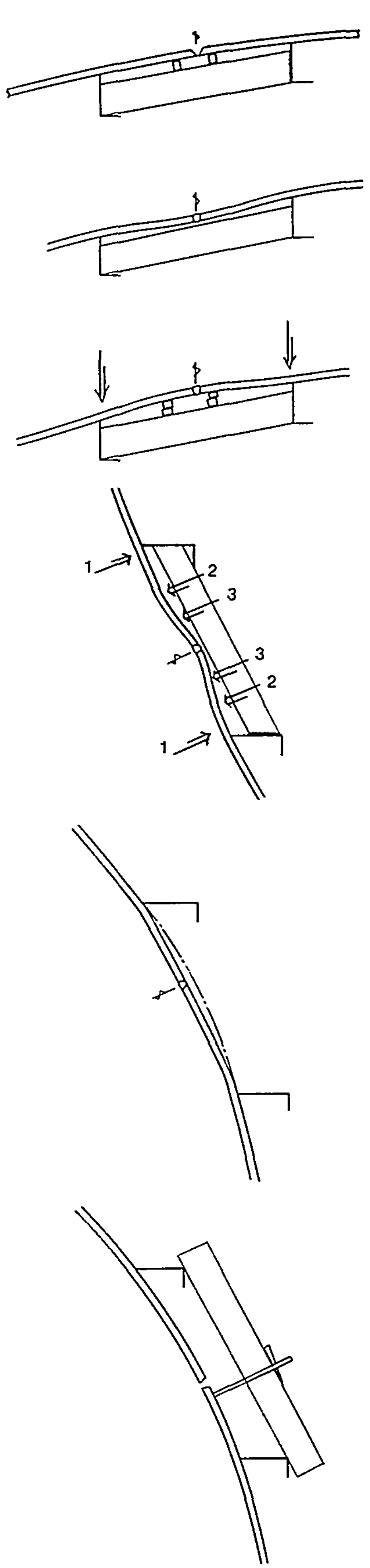


FIGURE 4-9. Straightening flat shell-plate about 1/4 inch thick and thicker. Thinner panels which distort more should be straightened as described for superstructure panels in *Figure 4-12.*



ASSUMPTION IS MADE THAT THERE WILL BE DEFORMATION CAUSED BY WELDING THUS THE STRONGBACK AND WEDGES USED FOR FITTING ARE RETAINED FOR FAIRING WORK.

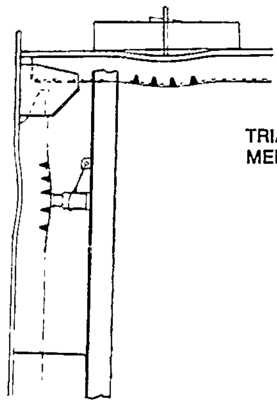
REMOVING THE WEDGES DISCLOSES IF DISTORTION EXISTS DUE TO WELDING.

THE WEDGES OR JACKS ARE THEN USED *TO* FORCE THE SHELL ABOUT 10 MILLIMETERS BEYOND THE MOLDED SURFACE AND LINEAR HEAT IS APPLIED TO THE BACK OF THE FILLET WELDS FOR FRAMES. THE WEDGES ARE LOOSENED AND THE PROCESS REPEATED AS NECESSARY.

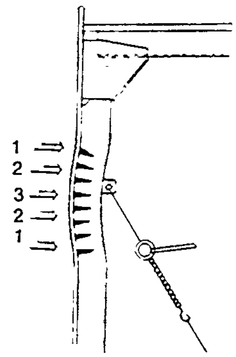
WHEN THE DISTORTION *EXTENDS* OVER AN ENTIRE PANEL LINEAR HEAT IS APPLIED TO THE BACK OF THE FILLET WELDS, 1 AND IF NECESSARY ALONG LINES 2 AND 3 WITH INTERMITTENT COOLING, USUALLY WEDGES OR JACKS ARE NOT REQUIRED. EXTREME CARE IS TAKEN TO FAIR IN MINUTE AMOUNTS TO AVOID SHIFTING THE PLATE BEYOND THE MOLDED SURFACE.

IF THE PLATE IS BEYOND THE MOLDED SURFACE AS SHOWN, THE WELD MUST BE CUT, THE PLATE EDGES MUST BE BUILT UP WITH WELD METAL AND THE PLATES REFITTED, OTHERWISE THE PROBLEM WILL REAPPEAR.

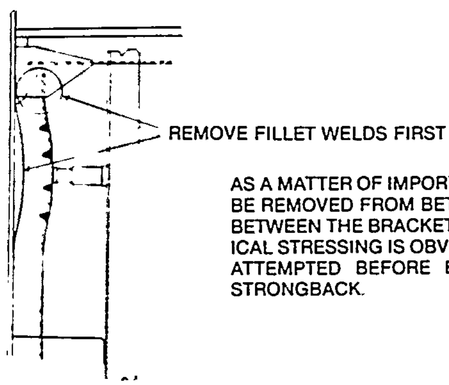
FIGURE 4-10: **Fairing curved-shell plate.**



TRIANGLE HEAT IS APPLIED TO SUPPLEMENT MECHANICAL STRESSING.



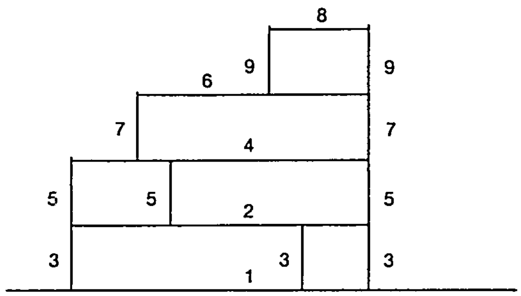
THIS TECHNIQUE EMPLOYS BOTH TRIANGLE HEAT ON THE STIFFENER AND LINEAR HEAT ON THE SHELL TO SUPPLEMENT MECHANICAL STRESSING.



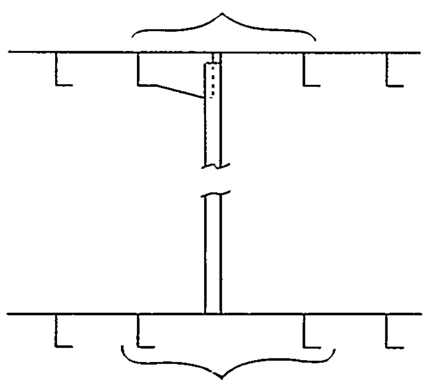
AS A MATTER OF IMPORTANCE THE FILLET WELDS SHOULD FIRST BE REMOVED FROM BETWEEN THE SHELL AND THE FRAME AND BETWEEN THE BRACKET AND THE FRAME. UNLESS THE MECHANICAL STRESSING IS OBVIOUSLY REQUIRED, TRIANGLE HEATING IS ATTEMPTED BEFORE EFFORT IS EXPENDED TO PLACE THE STRONGBACK.

DEFORMED BRACKETS ARE LINE HEATED AS SHOWN ACCOMPANIED BY MECHANICAL STRESS APPLIED BY HAMMER OR JIG IF NEEDED

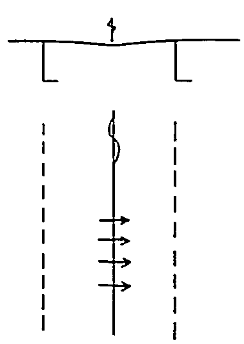
FIGURE 4-11: Fairing stiffeners and brackets for shell, decks, etc., when distortion is not very great.



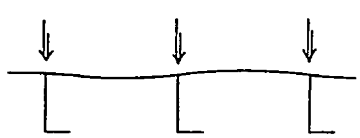
THE SEQUENCE SHOWN INCORPORATES A PATTERN STARTING AT THE BOTTOM, i.e., DECK BELOW, DECK ABOVE AND BULKHEADS IN BETWEEN.



SCHEDULING CONTINGENCIES SOMETIMES REQUIRED STRAIGHTENING BULKHEADS, SUCH AS FOR SHOWER SPACES, BEFORE DECKS ARE COMPLETED. IN SUCH CASES AT LEAST THE DECKS BETWEEN TWO FRAMES ENCOMPASSING THE BULKHEAD ARE STRAIGHTENED BEFORE STARTING WORK ON THE BULKHEAD

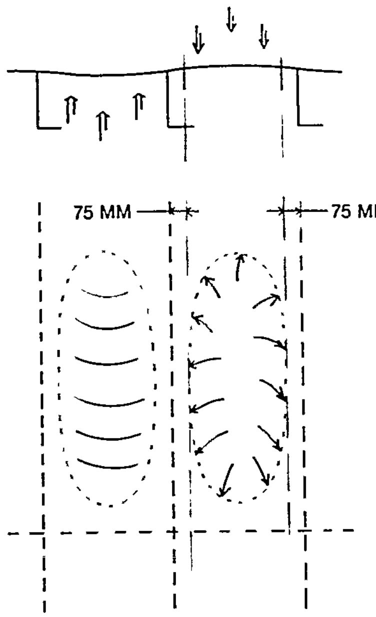


DISTORTION IS REMOVED FROM SEAMS BEFORE OTHER STRAIGHTENING IS STARTED.

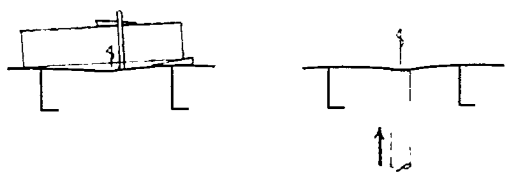


BECAUSE DECK PLATES ARE RELATIVELY THIN, ONE HEAT LINE ON THE BACK OF FILLET WELDS FOR EACH STIFFENER IS USUALLY SUFFICIENT FOR DISTORTION IN THE ORDER OF 10 MILLIMETERS.

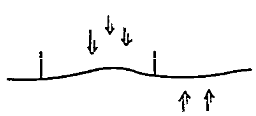
FIGURE 4-12 (a): Straightening superstructure decks and bulkheads.



FOR GREATER DISTORTION THE WORK DESCRIBED IN THE FOREGOING IS SUPPLEMENTED WITH PINE-LEAF HEATING AS SHOWN. EACH SUCH PASS STARTS WITH A SLIGHT PAUSE, THENCE UNIFORM TRAVEL OUTWARD AND SUDDEN REMOVAL OF THE TORCH. THE HEATING PROCESS STARTS AT THE PERIPHERY OF THE OVAL ZONE SHOWN AND THEN SUCCEEDING PASSES ARE LOCATED CLOSER TO THE CENTER. CARE IS TAKEN TO AVOID COMING WITHIN 75 MILLIMETERS OF STIFFENERS. ALSO, REGARDLESS OF WATER COOLING ABOUT ONE HOUR IS ALLOWED AFTER FAIRING BEFORE CHECKING TO DETERMINE IF ADDITIONAL FAIRING WORK IS NEEDED.



STRONGBACKS AND SHORES ARE SOMETIMES NEEDED TO APPLY MECHANICAL STRESS BEFORE HEATING. OFTEN, SUCH DEVICES ARE MORE PRODUCTIVELY EMPLOYED IF USED IN CONJUNCTION WITH HYDRAULIC JACKS FITTED WITH ELECTRIC-DRIVEN PUMPS.



BULKHEADS ARE STRAIGHTENED JUST AS ARE DECKS. AS SHOWN CARE IS TAKEN TO AVOID HEATING WITHIN 150 MILLIMETERS OF A DECK. ALSO FOR PLATE LESS THAN 5 MILLIMETERS IN THICKNESS SPOT HEATING IS OFTEN USED.

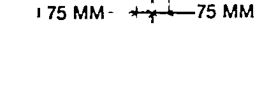
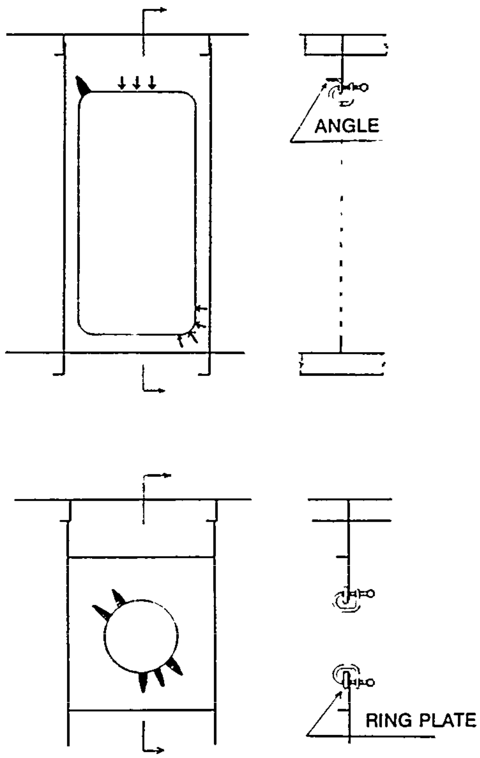


FIGURE 4-12 (b): Straightening superstructure decks and bulkheads.

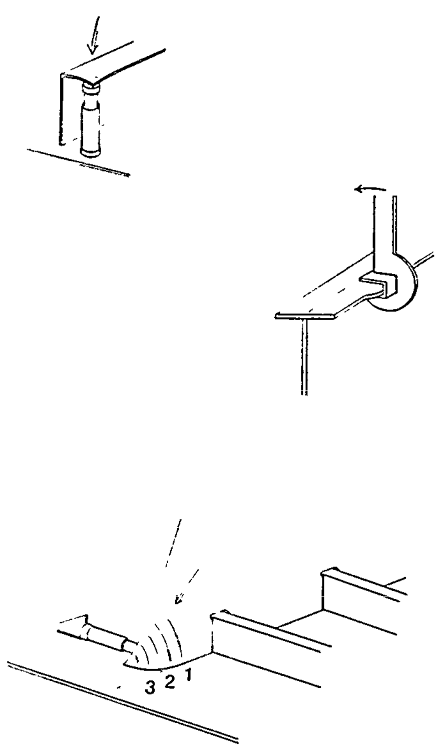


DECKS, BULKHEADS AND THEIR STIFFENERS ARE STRAIGHTENED BEFOREHAND.

A CARPENTER'S SQUARE IS USED TO ASSESS DISTORTION TRIANGLE OR LINE HEAT IS APPLIED AS SHOWN.

USUALLY JUST HEATING PROCESSES ARE SUFFICIENT BUT SOMETIMES MECHANICAL STRESSING IS REQUIRED.

FIGURE 4-13: Straightening the edges of openings.



GENERALLY, MECHANICAL METHODS ARE SUFFICIENT. SOMETIMES THEY ARE SUPPLEMENTED WITH RED-HOT HEATING.

WHEN HEAT IS NECESSARY, IT IS APPLIED ALONG CIRCULAR PATHS OF DECREASING RADII SEQUENCED AS SHOWN.

FIGURE 4-14: Correcting extreme distortion.

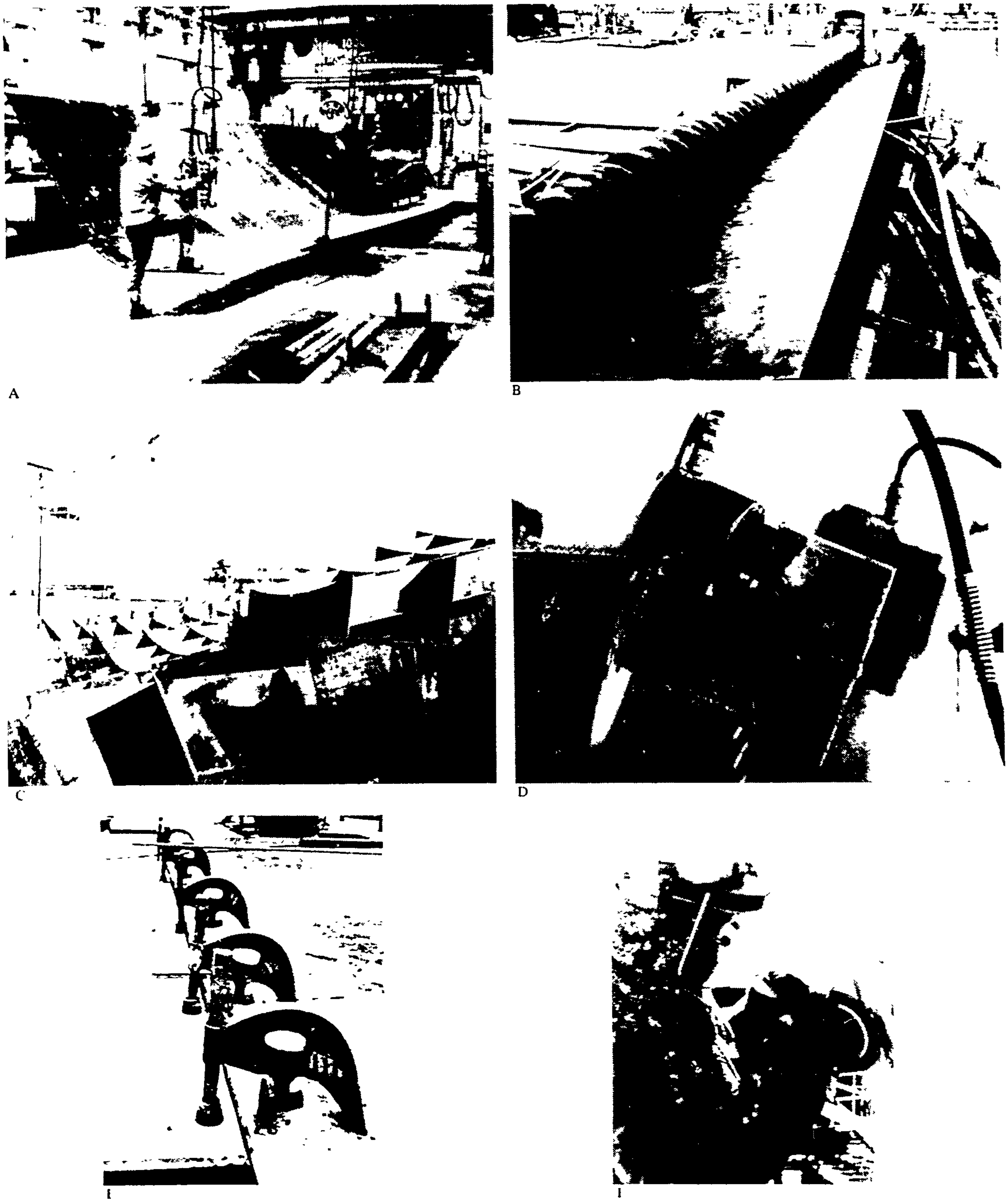


FIGURE 5-1 Line heating, both by itself and also in conjunction with presses (A) and rollers (B) is used to accurately produce curved parts. The process has eliminated the need for blacksmithing, e.g., hammering or pressing furnaced plates on extremely expensive 3-dimensional plate-forming jigs (C). Beyond the production of parts, there are even greater savings in assembly work, particularly where statistical control of accuracy is practiced. Because of improved accuracy there is less need for traditional shipfitting devices (D & E) which create the locked-in stresses which cause distortion after welding. Moreover, work associated with removing the devices and restoring plate surfaces (F) is also reduced.

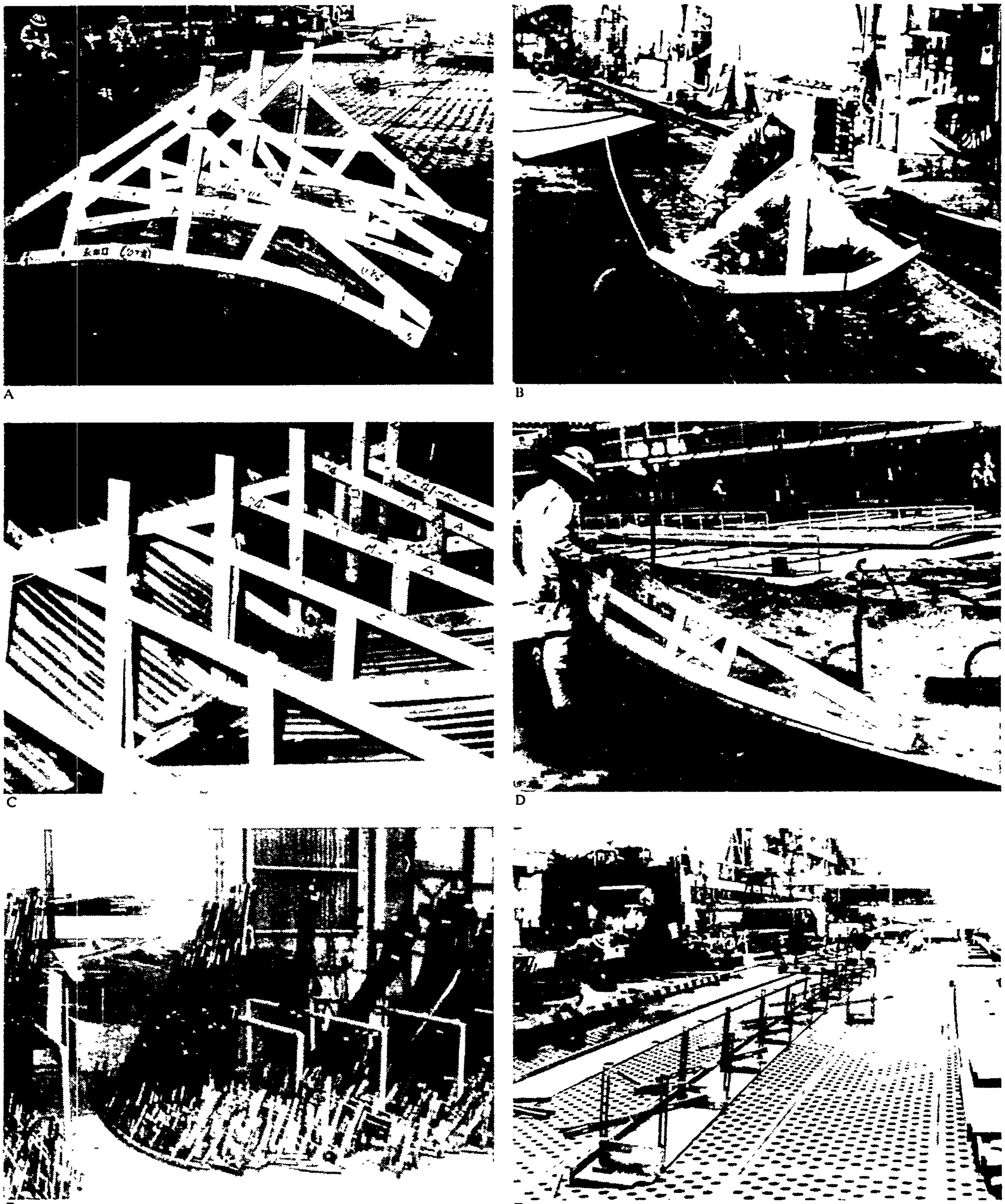


FIGURE 5-2: Following the development of line heating for curving parts, accuracy control techniques disclosed that variations in such parts were still the source of much distortion preventing productivity gains in assembly processes. In accordance with statistical-control theory applied to manufacturing, managers distinguished between variations caused by workers and those caused by the manufacturing system. Examination of the latter led to development of sets of special templates which enable workers to know exactly what curvatures are required. Sight-line templates featuring spatial inverse-curves are applied to various plate shapes (A, B & C) as are edge templates (D). Adjustable templates, shown awaiting use, are reusable (E). Sight-line templates are also in use for twisting longitudinals (F).

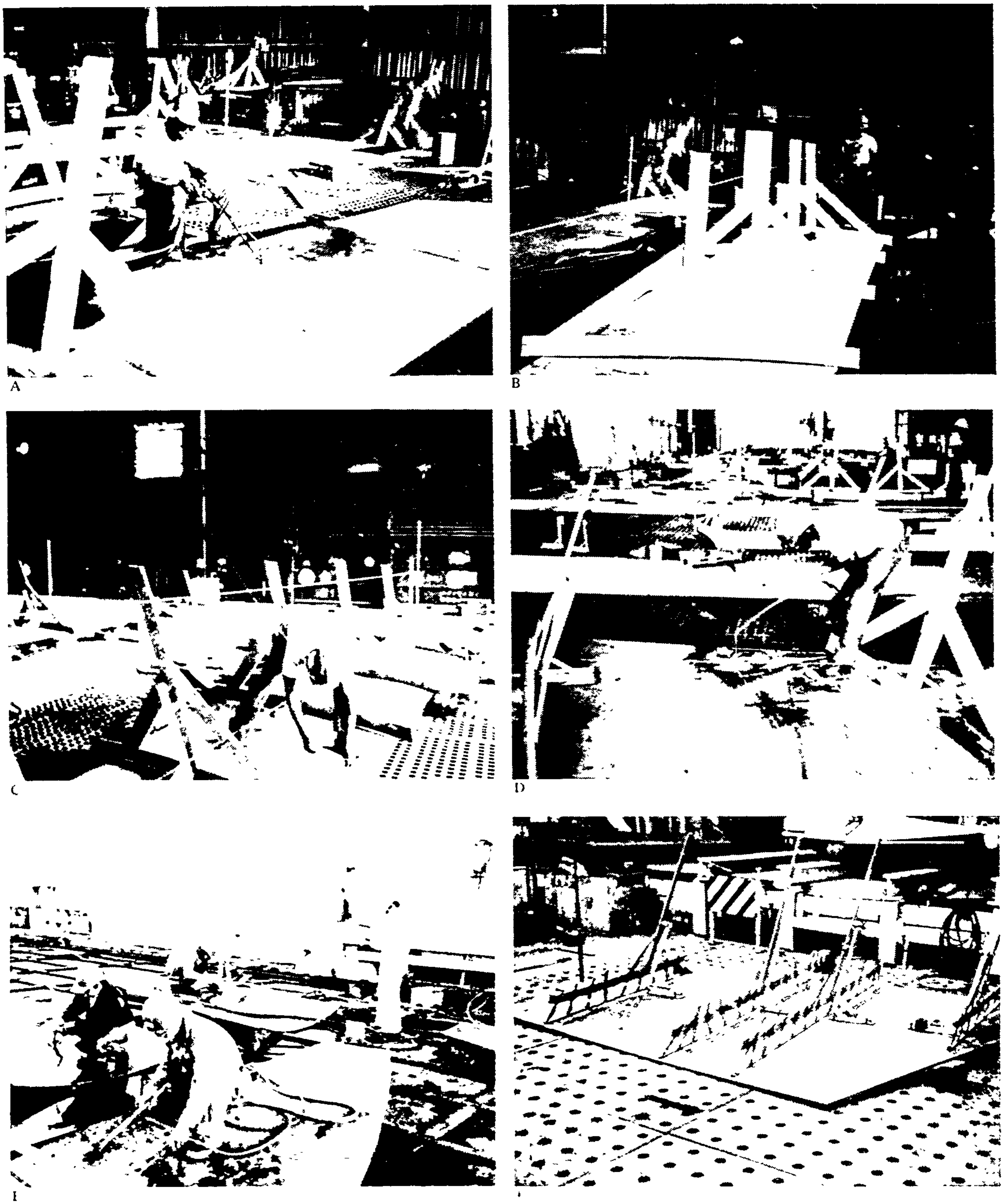


FIGURE 5-3: In Avondale Shipyards, Inc., longitudinal curvature is being applied to a plate which already has transverse curvature (A). Care is taken to avoid overbending. The sight-line templates are reset to assess the locations and amounts of finish heating necessary. Finish heating is needed to move the sight-point at each frame further down into alignment with the sight line represented by the taut string fixed between the sight points of the end templates (B). A second string below, aids in the alignment of sight edges. Additional transverse heat lines are marked (C) and finish heating is applied accordingly (D). In Lockheed Shipbuilding and Construction Co., plates for a bulbous bow are formed by line heating (E). Where fully exploited, even plates with little or no curvature and a small amount of twist are formed by line heating in order to minimize locked-in stresses during assembly work (F).

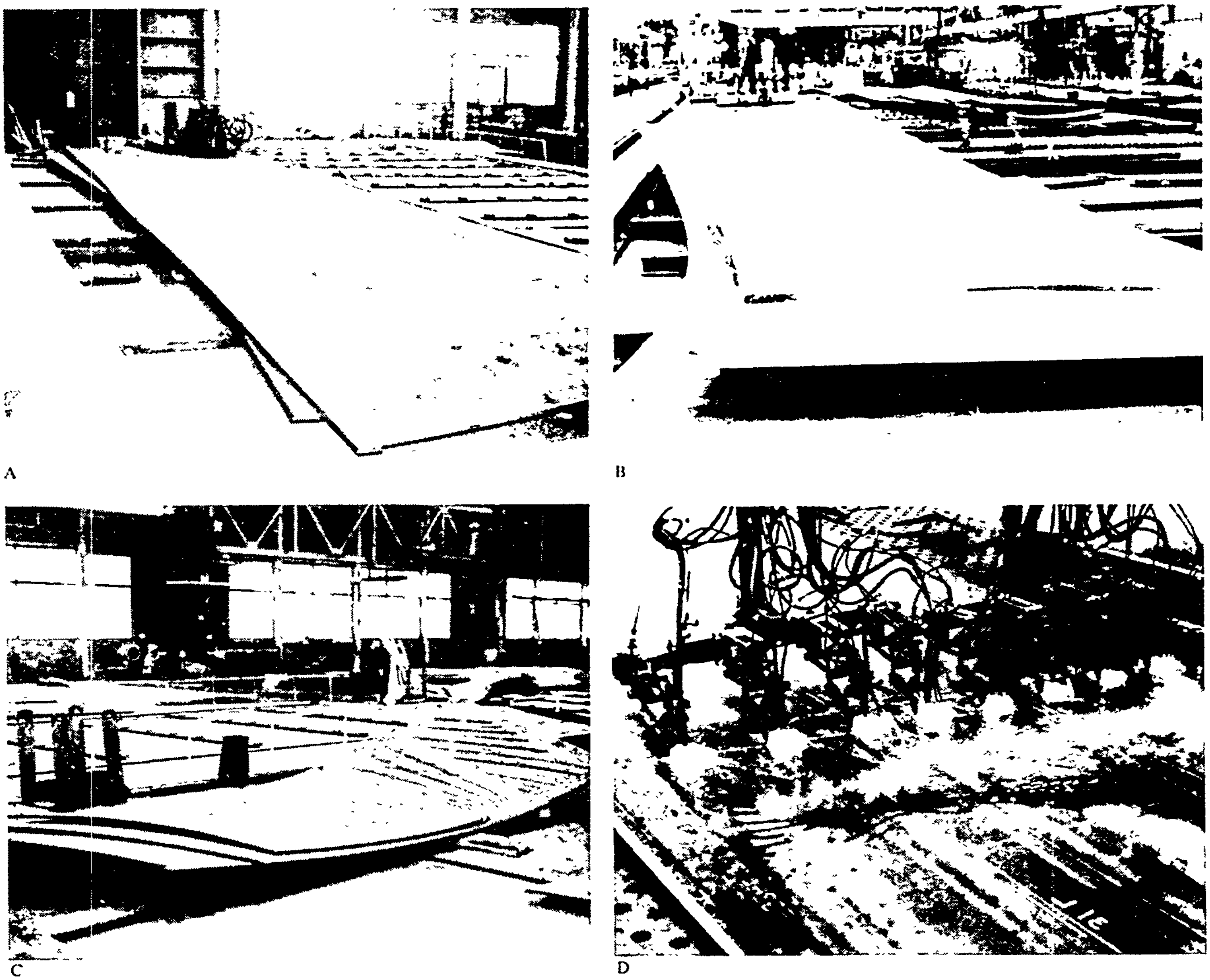


FIGURE 5-4: Initial curvature of side-shell plates is sometimes performed by press or roller and sometimes by line heating dependent on the nature and degree of curvature required and scheduling considerations. Finishing is always performed by line heating. Roll axes or press lines are seen on a plate finished with line heating (A). The process is not limited by furnace size nor by press or roller capacity, thus relatively large plates may be accurately curved (B) including those which butt the stem (C). When the process is automated (D), port and starboard plates are formed simultaneously with the same set of sight-line templates.

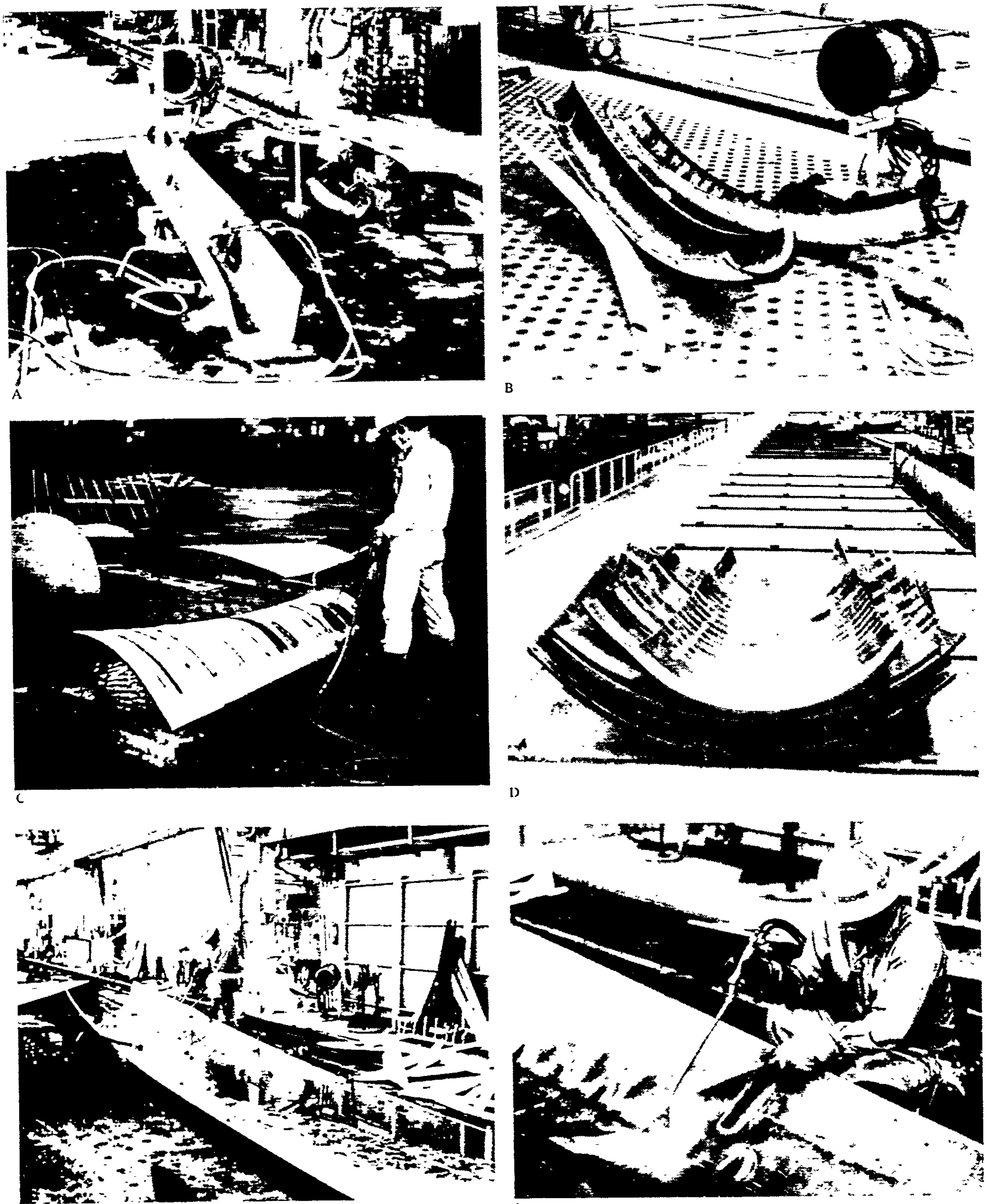


FIGURE 5-5: Following pressing, line heating is used to achieve accurate compound curvature in complex shapes such as for a: stem (A), lower stem (B), saddle (C), cant (D) and skeg (E). A detail of the latter shows a peculiar heating pattern along and across the knuckle (F).

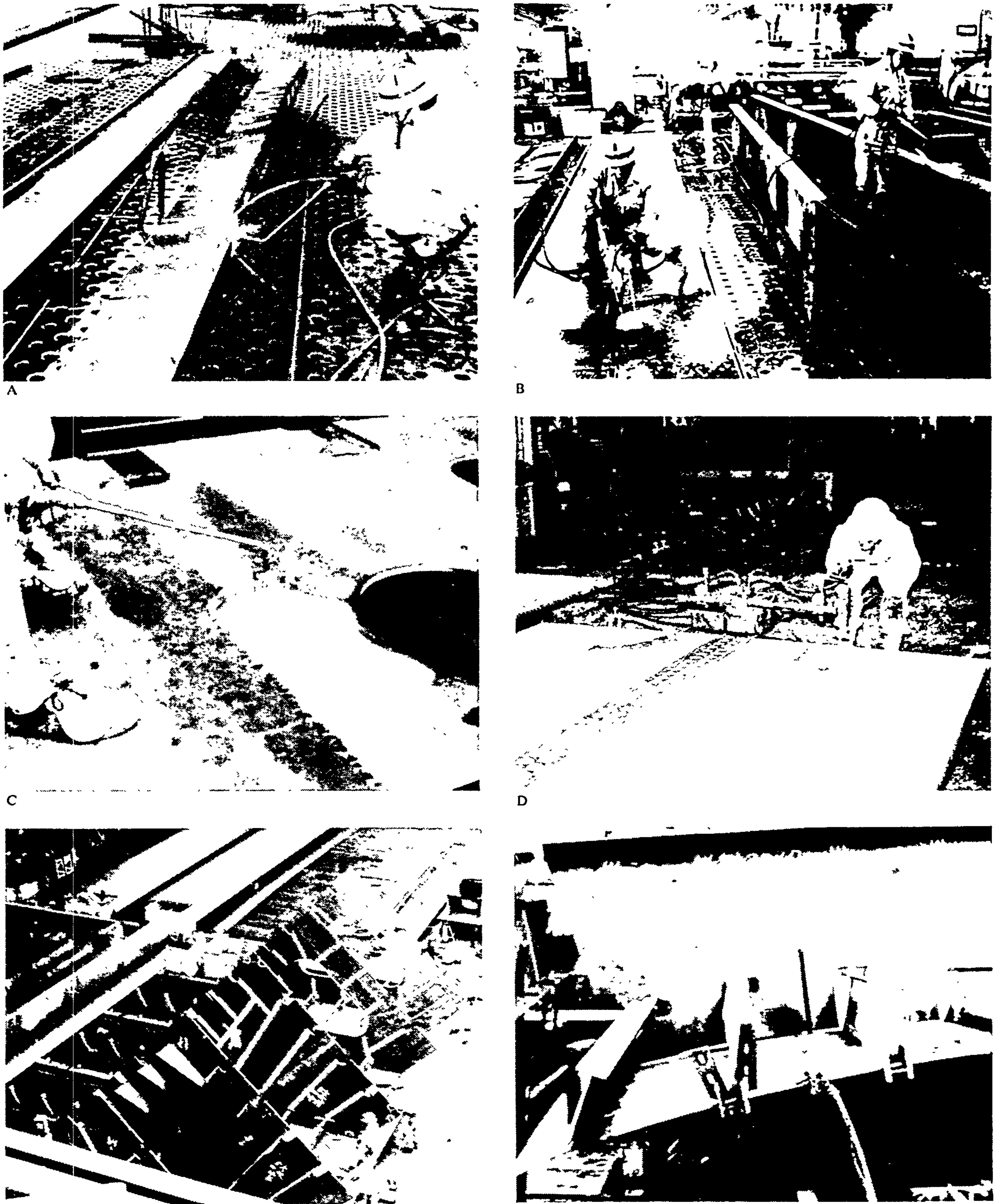


FIGURE 5-6: Line and its variation triangle heating are routinely applied for both straightening and twisting longitudinals (A) and for removing distortion from built-up parts (B) and sub-blocks (C & D) in order to facilitate block assembly (E & F). In the latter photograph which shows assembly of a curved block on a pin jig, heat marks appear on the shell, longitudinals and web. To further enhance accuracy, jigs are used to maintain longitudinals at prescribed angles and at a specified distance from the shell edge. The multiple torch tips shown in photographs C and D are noteworthy.

A B C D

FIGURE 5-7 Deck and bulkhead panels are heated opposite from fillet welds some distance back from butts (A). Similarly, line heating is used to remove distortion from a hatch coaming after its assembly (B). As a matter of utmost importance line heating is used to fair butts and seams of blocks before they arrive at the building dock (C & D).

FIGURE 5-8: The pine-leaf heating method is applied to fair superstructure bulkheads (A). Such heating is always applied to the convex side of the distorted panel. Light discolorations show where heat was applied from the inside. The dark discolorations shown where heating was performed from the outside. Linear heating is applied for correcting more extreme distortion in such panels (B). Linear heating is also applied across seams of superstructure decks (C) and a pine-leaf pattern is applied to straighten deck panels (D).

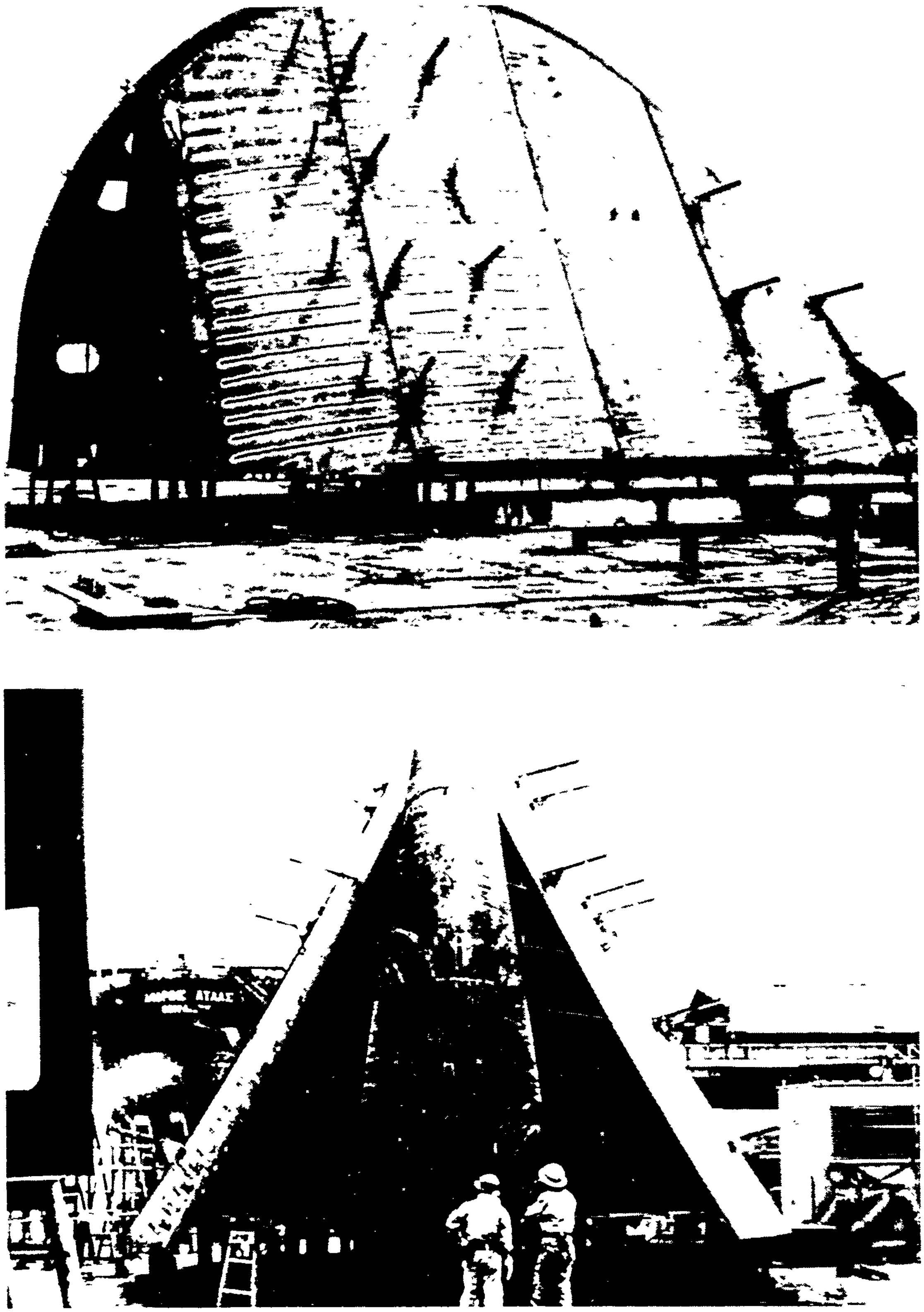


FIGURE 5-9. Specialization by problem categories, the essence of group technology, is manifested by a product work breakdown. Such planning enables manufacturers to identify different products which can be treated as if they were the same because the problems imposed by their manufacture are the same. Very different interim products, such as parts and subassemblies which characterize shipbuilding, are manufactured with production-line benefits. Variations in the performance of such work, disclosed by statistical monitoring and analysis of accuracy, stimulate constant perfection of design details, organization of work, and work processes. Existing shipbuilding systems which feature a product work breakdown, statistical methods for process analysis via accuracy control and *line heating*, accurately and productively produce any shape required for hydrodynamic, strength or esthetic purposes.

APPENDIX A

American Bureau of Shipping

Sixty-five Broadway

New York, N. Y. 10006

Refer to PS/gm

20 January 1982

Subject: National Shipbuilding Research Program; Line Heating

Attention: Mr. L. D. Chirillo

Gentlemen:

We have received your letter of 14 October 1981 together with the enclosure relative to the subject and in regard thereto we would advise as follows:

Line heating is permitted on all ABS grades of steel where it is demonstrated to the Bureau's satisfaction that the line heating procedure as used by the shipyard will not result in excessive degradation of material properties particularly in respect to tensile and charpy impact properties.

We believe it to be undesirable to heat the steel to an intercritical temperature. In general, we have approved procedures to a maximum heating temperature of 650°C. In an isolated instance, a procedure using temperatures above 6500C have been approved when used with appropriate equipment and technique. However, in general these higher temperaturesmay result in localized melting or excessive degradation of base plate.

We have attached excerpt of IIW X - 696-73 and X-695-73 which lists recommended limitations with regard to temperature for your reference.

Very truly yours,

AMERICAN BUREAU OF SHIPPING

W. M. Hannan
Vice President

By

I. L. Stern
Asst. Chief Surveyor
Materials Engineering Section

Enclosure

Editor's note: The excerpts consisted of pages 9, 10 and 12 from IIW document X-696-73 and page 9 from X-695-73. Items (1), (2) and (3) on page 10 of the former were marked for particular attention. The excerpts noted are reproduced in this Appendix supplemented by title pages, abstracts, introductions, conclusions, acknowledgements and references. Complete copies and other such documents are available from: American Council of the International Institute of Welding, Office of the American Council, P.O. Box 351040, Miami, FL 33135 (Tel: 305-642-7090).

IIVV DOC. NO. X–696–73

EFFECT OF FABRICATING PROCEDURES IN ASSEMBLING OF SHIP HULL STRUCTURE ON NOTCH TOUGHNESS OF STEEL PLATES (REPORT No .3)

– EFFECT OF LINE-HEATING CONDITION ON NOTCH TOUGHNESS OF STEEL PLATES –

March, 1973

BY

Hiroshi KIHARA * Jiro SUHARA **

Tsuneo KUROKAWA *** Shigeo KATAOKA ***

Hiroshi YAJIMA **** Tatsuro FUKAE ****

* Osaka University

** Kyushu University

*** Nagasaki Uuiversity

**** Mitsubishi Heavy Industries, Ltd.

EFFECT OF FABRICATING PROCEDURES IN ASSEMBLING OF SHIP HULL STRUCTURE ON NOTCH TOUGHNESS OF STEEL PLATES (REPORT NO. 3)

— EFFECT OF LINE HEATING CONDITION ON NOTCH ToUGHNESS OF STEEL PLATES —

BY

Hiroshi KIHARA * Jiro SUHARA **

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Hiroshi YAJIMA **** Taturo FUKAE ****

ABSTRACT

It is inevitable that 50 kg/mm^2 class high strength steels Suffer from some embrittlement when they are subjected to bending by the line-heating process. The embrittlement, however, is localized in some limited zone of the plate thickness. Therefore, it is a problem to estimate the notch toughness of the line-heated zone by Charpy V-notch impact test as generally performed.

In this study, an investigation was made to find the behaviour of the full thickness of the plates to the characteristics of brittle fracture initiation (by Deep Notchtest) and crack propagation-arrest (by Double Tension and ESSO tests) at the line-heated zone, using large-sized test specimens including full thickness plate.

The results of the above-mentioned tests are examined about criterions of $vTrs$, ${}_{16}T_{tc=10}$, ${}_{16}T_{aK=[illegible]}$ and ${}_{15}T_{aK=[illegible]}$. Consequently, having control of cooling condition, the more efficient conditions of line-heating than the actually suggested ones are obtained without

The line-heating conditions are outlined as follows,

1) In air-cooling after heating. there is no unfavourable effect observed even if the heating temperature is as high as 800°C or 900°C.

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**** Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltb.

2) In water-cooling immediately after heating, there is no unfavourable effect 2
observed when the heating temperature is as high as 650°C.

3) In water-cooling during air-cooling after heating, there is comparatively little unfavorable effect observed when the heating, a temperature is 800°C or 900°C, as long as a temperature at the start of water-cooling is below 500°C.

1. INTRODUCTION

It is needless to say that, in the determination of line-heating conditions of steel plates, the effect of heating on the properties of steel plates should be thoroughly considered. In case of 50 kg/mm^2 class high strength steel of which is used for hull plates have been more expanded, heating at a temperature higher than the transformation point Ac_1 or heating and water-cooling from higher temperature produces larger effect on notch toughness than in case of mild steel, and therefore such a safety measure, which is considered to be more than necessity, is taken as heating at a temperature lower than the transformation point and air-cooling further. However, since these conditions are inefficient as a practice of thermoplastic bending, it is desirable to obtain better bending efficiency by raising the heating temperature and to improve work efficiency by water-cooling.

The line-heating conditions have been usually determined on the basis of the results of the Charpy V-notch impact test taken from the vicinity of the heated surface. However, especially in thick plates, it is considered to be unreasonable that the safety of full thickness of heated plate for preventing of the brittle fracture is examined on the basis of local toughness. That is, a locally embrittled zone quite near the heated plate surface, if any, may not prevent the plate being put to practical use so long as the ratio of embrittled part to the full thickness of the plate is not too large.

In this study, the brittle fracture tests were performed using reliable large specimen for full thickness of plates to grasp quantitatively the relationships between the line-heating conditions and the characteristics of brittle crack initiation and propagation-arrest in the heated zone, and the proper conditions of the line-heating process were examined on the basis of the test results.

values of applied stress for Grade D and Grade E steels required by the standard of the Nippon Kaiji Kyokai[4] are used: i.e. for K5D steel (30 mm thick), applied stress of 16.0 kg/mm² and arresting critical crack length of 60 mm, in other words, the temperature ${}_{16}T_{aKc=220}$ satisfying the required K_c value 220 kg$\sqrt{\text{mm}}$/mm², and for K5E steel (30 mm thick), applied stress of 16.0 kg/mm² and arresting critical crack length of 240 mm, i.e. the temperature ${}_{16}T_{aKc=439}$ satisfying the required K_c value 439 kg$\sqrt{\text{mm}}$/ mm². In the meantime, for K5A steel (30 mm thick) and K5D steel (12.7 mm thick), same standrd as that for K5D (30 mm thick) is to be used.

It is considered that, in such steels as those used in this study, the maximum values of actual deviation to the standard temperatures due to the scattering of material properties will be within 20°C for vTrs and within 10°C for ${}_{16}T_{tc=10}$, ${}_{16}T_{aKc=220}$ and ${}_{16}T_{aKc=439}$. It may be, therefore, interpreted that, if each of the above-mentioned standard temperatures exceeds the range of the deviation to turn to higher temperature by line-heating, an evidently unfavorable effect on notch toughness is recognized.

The vTrs ${}_{16}T_{tc=10}$, ${}_{16}T_{aKc=220}$ and ${}_{16}T_{aKc=439}$ obtained from the plates line-heated under different conditions are shown in Fig. 14~Fig. 17.

From Fig. 14 ~ Fig. 17, the followig outline has been clarified, though not same in all types of steels. It may be said that steel plates, even if heated at a temperature higher than the transformation point Ac_1, 800°C~900°C, are not involved with embrittlement as long as air-cooled after heating, or water-cooled, starting at around temperatures lower than the transformation point Ar_1, approximately 500°C. In case where the plates are heated below the transformation point Ac_1, 600°C~650°C, clear embrittlement may not be recognized, either, even if those are water-cooled immediately after heating.

4. CONCLUSIONS

The characteristics of brittle crack initiation and propagation-arrest in 50 kg/mm² class high strength steels for hull plates. Grade A steel (K5A, 30 mm thick) Grade D steels (K5D, 30 mm and 12.7 mm thick) and Grade E steel (K 5E, 30 mm thick), were grasped for full thickness of plate at the line-heated zone by such procedures that, after heating by gas torch at different temperatures up to 1000°C at the point of 1.0 mm underneath of heated surface, the plates were line-heated under different cooling conditions.

It has been clarified that the following is the desirable conditions for line-heating 10
process so as not to have clearly unfavorable effect on the characteristics of brittle crack initiation and propagation-arrest:

(1) The heating temperature can be raised up to 800°C-900°C in case of air-cooling after heating.

(2) The heating temperature must not exceed 600°C-650°C in case of water-cooling immediately after heating.

(3) The heating temperature can be raised up to 800 C~900°C in case of water-cooling after a certain period of air cooling. however. the starting temperature of water-cooling should be below 500°C.

It has been thus clarified that the line-heating process in 50 kg/mm^{2}class high strength steel causes practically unfavorable effect on the notch toughness of the steel by controlling cooling conditions. but it is possible to moderate the present used conditions, and to improve the bending efficiency and workability by raising the heating temperature in addition to water-cooling.

ACKNOWLEDGEMENTS

This study was pointed UP by the Shipbuilding process Research Commitee in the Society Naval Architects of Japan and performed by the Research Section of the Japan Shipbuilding Research Association.

The authors wish to express their gratitude to the members of the said two organizations for the valuable suggestions and enthusiastic cooperation, and also to gentlemen who made their effort to perfom these tests, i.e. Mr. Takeshi Kubo of Department of Structural Engineering, Facutly of Engineering, Nagasaki University, Mr. Takahiro Hino, Mr. Tomonobu Kawabe and Mr. Kaneyasu Ishikawa of Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltd.

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2) H. Kihara, J. Suhara, T. Kurokawa. S. Kataoka, M. Nakajima, and H. Yajima "Effect of Fabricating Procedures in Assembling of Ship Hull Structure on Notch Toughness of Steel Plates (Report No. 2) — Thermoplastic Deformation and Local Brittlement due to Line-Heating" —, IIW DOC. No.X--695-73.

3) H. Kihara, T. Kanazawa, K. Ikeda, H. Maenaka, M. Kinoshita, R. Nagamoto and H. Yajima: "Effectiveness of Crack Arrester (2nd Report)", J. Sot. Naval Arch. Japan, Vol. 124, 1968.

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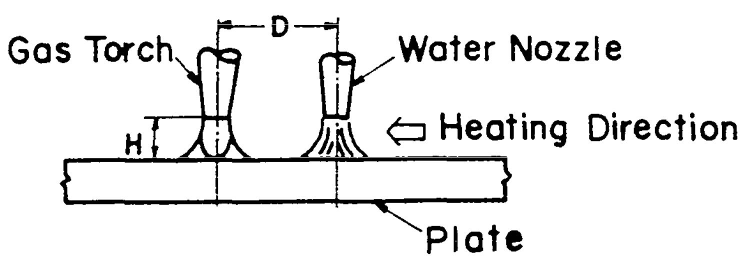
Table 1 Chemical compositions and mechanical properties of steel used

Specification	Heat Treatment	Plate Thickness (mm)	Chemical Compositions (%)					Tensile Properties		
			C	Si	Mn	P	S	Y.P kg/mm²	T.S kg/mm²	Elong. (%) G.L 200 mm
K 5 A	As Rolled	30	0.12	0.34	1.24	0.025	0.020	37.8	52.4	25.2
K 5 D	Normalized	30	0.15	0.46	1.31	0.014	0.019	36.0	53.0	[illegible]
K 5 E	Normalized	30	0.13	0.35	1.35	0.027	0.017	38.2	55.1	23.7
K 5 D	As Rolled	12.7	0.15	0.46	1.31	0.014	0.019	39.0	55.0	[illegible]

Table 2 Conditions of line-heating.

Item	Condition
Nozzle of Gas Torch	2.8 mm$^{\phi}$
Pressure of Oxygen	6.0 kg/cm²
Flow Rate of Oxygen	2.3×10^{3} ℓ/h
Pressure of Acetylene	0.5 kg/cm²
Flow Rate of Acetylene	2.0×10^{3} ℓ/h
Height of Gas Torch (H)	20 mm
Distance between Gas Torch and Water Nozzle (D)	Min.50 mm
Flow Rate of Water	2.3 ℓ/min



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EFFECT OF FABRICATING PROCEDURES IN ASSEMBLING OF SHIP HULL STRUCTURE ON NOTCH TOUGHNESS OF STEEL PLATES (REPORT NO. 2)

— THERMOPLASTIC DEFORMATION AND LOCAL BRITTLENESS DUE TO LINE-HEATING —

March, 1973

BY

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EFFECT OF FABRICATING PROCEDURES IN ASSEMBLING OF SHIP HULL STRUCTURE ON NOTCH TOUGHNESS OF STEEL PLATES (REPORT NO.2)

— THERMOPLASTIC DEFORMATION AND LOCAL BRITTLENESS DUE TO LINE-HEATING —

BY

Hiroshi KIHARA * Jiro SUHARA **

Tsuneo KUROKAWA *** Shigeo KATAOKA ***

Masaki NAKAJIMA **** Hiroshi YAJIMA ****

ABSTRACT

Line-heating is a thermoplastic working technique widely applied to bending and straightening of hull plates in shipbuilding.

In this study, the thermoplastic deformation and the local brittleness due to line-heating for 50 kg/mm^2 class high strength steels were investigated by Charpy V-notch impact test, hardness test and observation of microstructure. The results obtained are as follows:

1) The relation between the line-heating condition and the thermoplastic deformation was clarified.

2) In the heating at a temperature exceeding the transformation point Ac_1, the air-cooling causes only little embrittlement.

3) In the water-cooling after heating, the embrittlement is comparatively slight if the starting temperature of water-cooling is kept below the transformation point Ar_1.

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1. INTRODUCTION

Line-heating is a thermoplastic working technique widely applied to bending and straightening of hull plates in shipbuilding.[1)]

For line-heating of mild steel plates, gas torch heating at a temperature higher than the transformation point Ac_1 and water-cooling is generally used. Meanwhile, for 50 kg/mm^2 class high strength steels, it is a generally accepted idea to heat the *steel* at a temperature *lower* than the transformation point Ac_1 at the maximum and to avoid water-cooling immediately after heating from the viewpoint of prevention of its embrittlement. However, reasonably accepted standard condition of line-heating has not been established practically.

Better bending efficiency is obtained by increasing the heating temperature, while more workability is expected by possibility of water-cooling immediately after heating. In this study, the thermoplastic deformation and the local embrittlement due to line-heating, obtained from the under-mentioned tests performed to determine the most efficient bending condition within the range of practically allowable embrittlement, are stated hereunder accompanied with the background data for establishment of the line-heating conditions thus obtained from the results of those tests.

2. TESTS

2.1 Line-Heating Conditions and Thermoplastic Deformations

2.1.1. Line-Heating Conditions

Line-heating is used in a shipbuilding process in Japanese shipyards, but the condition varies in each firm. In this study, the line-heating conditions shown in Table 1 were taken up in accordance with the intensive answers to questionnaires) issued to each shipyard on like process conditions. The height of gas torch nozzle from the specimens surface to be heated were S0 adjusted to be 20 mm as shown in Table 1, that the tip of incandescent flame might touch the surface to produce the maximum temperature of heating flame.

The method of heating was straight line-heating with gas torch and cooling water nozzle mounted on a carriage. The relationship between the torch travel speed and the maximum heating temperature is shown in Fig. 1. The temperatures were measured with an electro-magnetic oscillograph connected to C.A. thermocouples of 0.3 mm diameter which were percussion welded to the bottom of a 1.5 mm diameter hole drilled from the back to 1.0 mm below the heated surface. Therefore. the maximum heating temperature shown in Fig. 1 represents the highest temperature

tion to turn to higher temperature by line-heating. the embrittlement due to the heating 9 is recognized.

Thus the Charpy V-notch impact test is estimated as follows.

K 5 A steel

(1) In air-cooling after heating even if at a temperature 900°C, there is not obvious embrittlement recognized.

(2) In water-cooling during air-cooling after heating at a temperature 800°C~900°C, there is embrittlement recognized regardless of the starting temperature of water-cooling, but it is hardly said that there is unfavorable effect observed.

(3) In water-cooling immediately after heating at a temperature 800°C, its v*Trs* is transferred to approximately 30°C higher side and there is a remarkable embrittlement recognized.

K 5 D steel

(1) In air-cooling after heating at a temperature as high as 1000°C, there is no remarkable embrittlement recognized.

(2) In water-cooling during air-cooling after heating at a temperature 800°C~900°C, there is no remarkable embrittlement recognized as long as the starting temperature of water-cooling is 500°C.

(3) In water-cooling immediately after heating, there is remarkable embrittlement recognized if the heating temperature is as high as 700°C.

K 5 E steel

(1) In air-cooling after heating, the embrittlement is comparatively slight if the heating temperature is kept below 700°C.

(2) If the heating temperature is over 800°C, there is embrittlement recognized regardless of water-cooling and air-cooling.

3.3. Difference of Embrittlement due to Line-Heating in K5A, K5D and K5E Steels.

It was found as mentioned above that the effect of line-heating performed even under the same condition, on embrittlement was different according to K 5A, K 5 D and K 5 E steels, especially the K 5 E steel seems to be larger than the other steel. This is considered due to that K 5 A and K 5 D steels and K 5 E steel are manufactured by different steel mills, therefore, the chemical compositions and conditions of rolling and heat treatment in the manufacturing process are not the same. Provided that the K 5 A steel is as rolled material, while the K 5 D and the K 5 E steels are normalized materials.

As far as the results of measurement of the transformation point Ac_1 are concerned, that of K 5 E steel is lower than that of K 5 D steel, while the transformation point Ar_1 of K 5 E steel tends to be transferred by faster cooling velocity to a lower temperature side than that of K 5 D steel. This phenomenon seems to be because of different contents of added elements and trace elements in each type of steel.

Therefore, since the pearlite in K 5 E steel is dissolved at a lower temperature than in K 5 D steel, the former is affected more by heating under the same condition. Meanwhile, the transformation in K 5 E steel is more delayed when cooled, resulting in larger quench hardening ability, and accordingly it is considered that the embrittlement in it is affected more than in K 5 D steel under the same heating condition.

4. CONCLUSIONS

The thermoplastic deformation and local embrittlement due to line-heating were quantitatively grasped for 50 kg/mm^2 class high strength steels for ship hull plates, Grade A steel (K 5 A), Grade D steel (K 5 D) and Grade E steel (K 5 E), and the following conclusions were obtained.

(1) The effect of straight line-heating conditions on thermoplastic deformation was clarified.

(2) In heating at a temperature above the transformation point Ac_1, there is little embrittlement in heated zone if air-cooled, while it is remarkably embrittled if water-cooled immediately after heating. The 50 % crystallinity transition temperature $vTrs$ obtained as the results of the Charpy V-notch impact test which was performed on heated surface, is transferred by immediate water-cooling to approximately 30°C higher side for the material.

(3) In water-cooling during air-cooling” after heating. the embrittlement in heated zone is comparatively little, if the water.cooling is started at a temperature below the transformation point Ar_1. The $vTrs$ of heated surface in K 5 A steel and K 5 D steel is transferred to approximately 10°C-20°C higher Side for the material and that in K 5 E steel to approximately 20° C~30°C higher side.

If the only effect of heated surface on notch loughness is considered from the above mentioned results. it is considered that the air-cooling after heating is most desirable. This conclusion is, however. obtained mainly from the examination of local toughness. like the Charpy V-notch impact test of line-heated surface. For the

examination and establishment of a line-heating standard for the field process, 11 therefore, it is recommended to consider thoroughly large-scaled test results in full plate thickness of heated zone which is regarded as showing the fracture strength more accurately.

ACKNOWLEDGEMENTS

This study was pointed by the Shipbuilding Process Committee in the Society of Naval Architects of Japan and performed by the Research Section of the Japan Shipbuilding Research Association.

The authors wish to express their gratitude to the members of the said two organizations for the valuable suggestions and enthusiastic cooperation, and also to those gentlemen who made their effort to peform these tests. i.e. Mr. Takeshi Kubo of Department of Structural Engineering, Faculty of Engineering, Nagasaki University, Mr. Shizuo Kawanami and Mr. Kaneyasu Ishikawa of Nagasaki Technical Institute, Mitsubishi Heavy Industries, Ltd.

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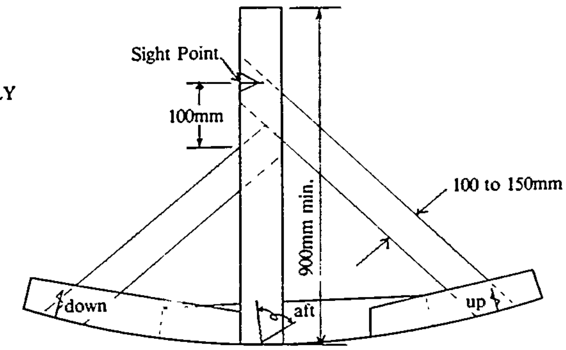
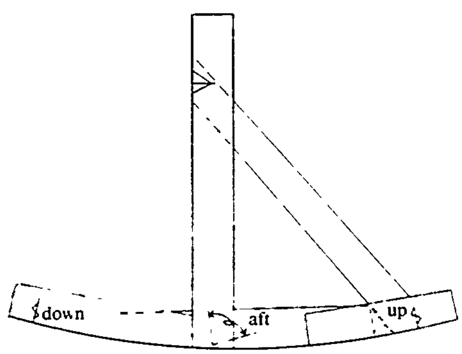
6) M. Inagaki, K. Nakahara, K. Harada, and Y. Mitani: “Notch Toughness in Welding Heat Reappearing Structure Around Bond Zones of High Tensile Strength Steels of Various Types”, Journal of Japan Welding Society, Vol. 33, No.9, 1964.

APPENDIX B
SIGHT-LINE TEMPLATES

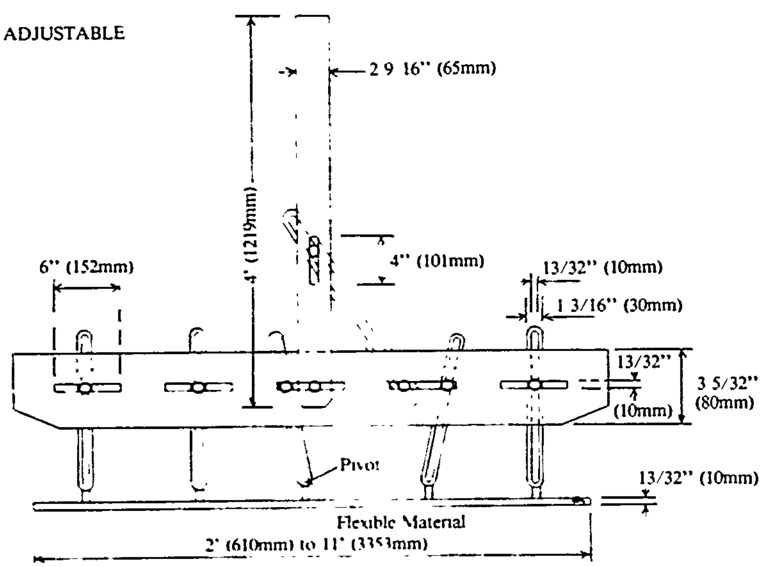
WOOD
RELATIVELY
LARGE



WOOD
RELATIVELY
SMALL



METAL ADJUSTABLE



APPENDIX C

I. Heating torches and tip sizes identified as satisfactory for line heating.

(1) For methane rich natural gas:

Maker: Tokyo Reinetsu Sangyo, Co.
6-3-18, Roppongi, Minatoki, Tokyo 105,
Japan
Tel. 03-478-2001

Torch: Line heating torch for city gas

Tip: #4000 M (4.5 mm ϕ)
#3000 M (4.0 mm ϕ)
#3000 S (3.5 mm ϕ)
#2500 S (3.3 mm ϕ)

(2) For propane gas:

Maker: Tanaka Engineering Works, Ltd.
11, Chikumazawa, Miyogi-cho, Iruma-gun,
Saitamaken, 354, Japan
Tel: 0492-58-4411

Torch: #565 Hi-power line heating torch

Tip: #6950-1500 (3.8 mm ϕ)
#6950-2000 (4.0 mm ϕ)
#6950-2500 (4.5 mm ϕ)

Maker: Koike Sanso Kogyo, Co., Ltd.
3-4-8, Taihei, Sumida-ku, Tokyo 130,
Japan
Tel: 03-624-3111

Torch: S-type heating torch
M-type heating torch

Tip: L-1000S (2.5 mm ϕ)
L-2000S (3.0 mm ϕ)
L-3000S (3.5 mm ϕ)
L-3000M (4.5 mm ϕ)
L-5000M (5.2 mm ϕ)

(4) For acetylene gas:

Maker: Tanaka Engineering Works, Ltd.

Torch: #168 Model-2 torch
#166 Model-3 torch

Tip: #6820-1000
#6820-3000
#6820-4000
#6620-30
#6620-40
#6620-50

II. Heating torch and tip sizes selected by an American shipyard relative to plate thicknesses.

Torch Mfgr. - Tanaka Engineering works Ltd.

Model - No. 6950

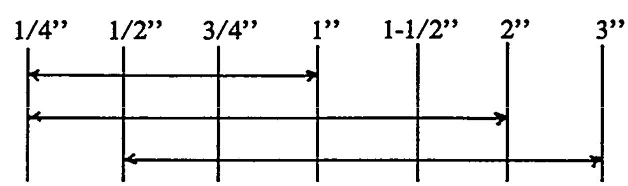
PLATE SIZES

TIP SIZES

No. 1500 = 3.8 mm ϕ

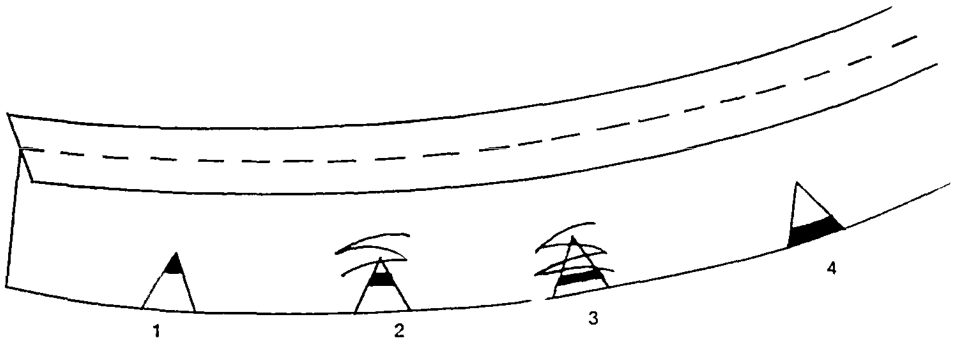
No. 2000 = 4.0 mm ϕ

No. 2500 = 4.5 mm ϕ



No.	**O_2 Pressure**	**Gas Propane**
No. 1500 - 3.8 mm ϕ	2 KG/CM²	0.4 KG/CM²
No. 2000 - 4.0 mm ϕ	3 KG/CM²	0.4 KG/CM²
No. 2500 - 4.5 mm ϕ	4 KG/CM²	0.4 KG/CM²

NOTE: American torch manufacturers can supply the equivalent torch models and equal tip sizes.



A Method for Triangle Heating

Steps

1 Heat is applied to about one inch of the apex before application of coolant.

2 After starting torch travel in a weaving motion, coolant if applied behind the heated region along arcs as shown. The coolant is not applied directly on or ahead of the heated region.

3 The same pattern is continued moving toward the edge while maintaining about one inch of hot metal ahead of the coolant.

4 On reaching the edge the coolant is stopped while heat is applied on the edge long enough for upset metal to shrink. Afterwards coolant is restarted.'